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CONTENTS OF VOLUME XXXI

NUMBER I

NUMBER II

NUMBER III

NUMBER IV

NUMBER V

NUMBER VI

NUMBER VII

NUMBER VIII

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The Pleistocene of Northwestern Illinois: a Graphic Presentation of the Chief Lines of Evidence. By MORRIS M. LEIGHTON.

Tilted Galena Dolomite over Fossiliferous Loess at the Border of Belvidere Lobe in Winnebago County, Illinois. By MORRIS M. LEIGHTON.

The Physical Chemistry of the Crystallization and Magmatic Differentiation of Igneous Rocks. VIII. By J. H. L. VOGT.

A Venerable Climatic Fallacy. By T. C. CHAMBERLIN.


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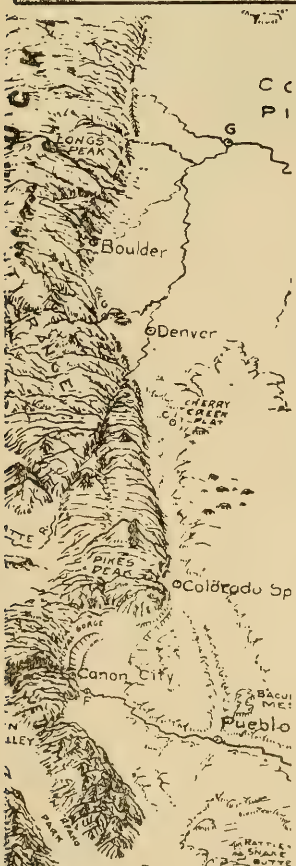
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VOLUME XXXI NUMBER 1

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January-February 1923

THE CYCLE OF EROSION AND THE SUMMIT LEVEL OF THE ALPS

W. M. DAVIS

CONTENTS

PART I. PENCK'S ESSAY ON THE SUMMIT LEVEL OF THE ALPS

A leading feature of the Alps.—An essay entitled "Die Gipfelflur der Alpen" by Professor Albrecht Penck[1] is of special interest on several counts. It discusses a striking feature of the most studied mountains in the world; it is written by the most accomplished geological geographer of Europe, whose acquaintance with his field is exceptionally intimate; it proposes several refinements of the cycle of erosion; and it employs deduction to an extent that, while unquestionably helpful, has been decried by certain other German geographers.

The subject under discussion is the relative constancy of altitudes in the higher ridges and peaks of the Alps. If one stands on a main summit, countless other summits rise like waves of the sea with crests of similar heights, in spite of the very dissimilar heights that the summits should have if they still represented the unequal deformational uplifts that the different parts of the range have suffered. Penck himself over thirty years ago explained the similar summit altitudes as marking an "upper limit of denudation," above which a mountain top could endure so short a time under the violent attack of the weather and the active removal of detritus on the over-steep slopes as to be rare occurrence.[2] He now extends his previous discussion, first by a more refined account of Alpine forms, in which he introduces an understanding of the effects of glacial erosion that had not been reached when his earlier article was written, and second by an elaborate deductive analysis of the cycle of erosion for mountains, in which the interaction of upheaval and degradation is more fully considered than has hitherto been done. His analysis is summarized in the following paragraphs, to which my comments are added in parentheses.

The preglacial form of the Alps.—The study of actual Alpine forms leads Penck to the conclusion that, as a rule, even if a typical mountain ridge were restored from its present extremely sharp form as given by glacial erosion to its preglacial form, its crest would have

[1] *Sitzungsber. preuss. Akad.*, XVII (Berlin, 1919), pp. 256–68.

[2] "Über Denudation der Erdoberfläche," *Schr. Ver. Verbr. nat. Kenntn.*, Vol. XXVII (Vienna, 1887), p. 431.

been fairly sharp, its sides would have had fairly uniform slopes of too steep an inclination for the retention of more than a thin sheet of creeping detritus, and its height over the adjacent valley bottoms would have been about half the horizontal distance from them, or a quarter of the distance between them. In other words, the ridge slopes must then have been essentially graded with respect to the principal streams. Under such conditions the degradation of the ridges would have still been in fairly rapid progress, and their altitudes would have been as nearly alike as the valleys between which they rose were equidistant. (This modifies and presumably improves a conclusion that Penck had reached eleven years earlier, when he thought that erosion under the leadership of the ancient glaciers had carved the present very sharp Alpine crests out of maturely rounded preglacial ridges.[1]) It is the origin of the sharp preglacial ridges of similar altitude and rapid degradation that is now sought for, and in this search the deductive analysis of several ideal cycles of mountain erosion is undertaken with the object of discovering at what stage of their progress and under what relations of upheaval and degradation the inferred uniform altitudes of the preglacial Alps can be best accounted for. Although the essay is the work of a geographer, the study as a whole is more largely concerned with conditions and processes of the past than with the forms of the present and hence its character is dominantly geological; and in this respect it is characteristic of German physiography in general.

First ideal cycle: Erosion during prolonged upheaval.—Three ideal cycles are examined. All begin with a mass of deformed structures, previously worn down to a lowland. Structural complications and differences of rock resistance are left out of consideration, presumably to simplify the problem. A broad upheaval

[1] . . . . "aus den reifen Firstformen jähe Grate herausschnitt." This statement is to be found on p. 154 of an admirable summary of the physiography of the lands as resulting from the interaction of deformation and erosion, entitled "Die Erdoberfläche," which makes the third chapter of Scobel's *Geographisches Handbuch*, 5th ed.; Leipzig, 1908. It will be referred to below as Sc., with page numbers. An interesting measure of the progress of rational geography may be had by comparing this chapter of 1908 with the corresponding chapter which Penck contributed to an earlier edition of the same work in 1895.

without marked deformation is assumed: it may be taken to have the form of a very broad dome. In the first ideal cycle, a gradual and long enduring upheaval is postulated. During an early stage, the initially flat interstream upland spaces will suffer little erosion and will consequently for a time gain in altitude about as much as they are upheaved. At the same time the depth of the young valleys, which the streams are rapidly incising beneath the flat uplands, must be less than the measure of upheaval. Hence at this stage both the absolute altitude and the local relief of the region are increasing. But as upheaval continues, and as the deepening valleys are opened by weathering, so that their side slopes will have a fairly uniform declivity, a stage must be reached when the flat uplands will be narrowed to sharp ridge crests (Schneiden), and on the attainment of this stage the altitude of the ridges will be as nearly constant as the valleys are evenly spaced. (This deduction depends on a general principle, according to which the height of a ridge crest above the neighboring valley bottoms will be a simple fraction—about a quarter, according to Penck—of the distance between the valleys, provided that the cliffs and ledges on the ridge sides are obliterated by the upward or retrogressive extension of graded slopes of fairly uniform declivity, from the banks of the streams at the valley bottoms all the way up to the ridge crests. Previous to the attainment of this graded stage, the occurrence of ungraded cliffs and ledges in the ridge sides would allow the ridge crests to have heights independent of the spacing of the valleys. Evidently, therefore, the less perfect the grading of the ridge sides from the streams up to the crests, the less perfect the control of crest height by valley spacing.)

During the continuance of this stage the deepening of the valleys in the rising mass will go on, but not yet fast enough to counterbalance the upheaval which is still in progress. The sharp ridge crests will no longer gain in altitude by the measure of upheaval, but only by that measure minus the rate of valley deepening; hence while crest altitude is now slowly increasing, local relief will remain constant. (In view of the fact that large streams grade their courses sooner than the side slopes of their valleys are graded, it seems necessary to assume that when the

valley sides are graded up to the ridge crests, as they must be if crest height is to be dependent on valley spacing according to the principle above cited, then the streams also must be graded, even though, on account of persistent upheaval, they are constantly degrading their graded courses and are therefore not yet permitted to widen their valley floors in flood plains: but this point is not mentioned in Penck's analysis. If the point be well taken, the postulated rate of upheaval should be conceived as rather moderate, even though it is specified as strong [stark]. It would further seem as if a very special though accidental relation must exist between rate of upheaval, climate, drainage area, and rock resistance, in order that the good-sized streams here considered should maintain a graded flow, and that their valleys should maintain graded slopes, even while upheaval is in progress. For it must be remembered that as the streams are not yet deepening their valleys as fast as the mountain mass is rising, their fall must be increasing; and with increasing fall, their graded condition might be lost. Besides, with increase of mountain height, there must be increase of rainfall and of stream volume; and increase of stream volume would still further promote a return to a youthful, non-graded condition rather than a persistence in a mature or graded condition. On the other hand, the increase in valley depth and the accompanying increase in the area of wasting valley sides—part of this second increase being due to the development of many side ravines—will cause an increase in the detrital load that is to be swept away by the streams; and this may permit them to develop graded courses in spite of their increased fall; but none of these details are mentioned in Penck's deductive analysis. In order to avoid misunderstanding, let it be explicitly stated that the introductory clause of this parenthical note does not apply to the small headwater streams of an uplifted peneplain; they deepen the valley heads so slowly that their side slopes are kept graded while the deepening is in progress.[1] It is only the larger streams that grade their beds before the valley sides are graded.)

Balance of upheaval and erosion.—Next comes a stage when the larger streams, which are supposed to be continually invigorated

[1] See my *Erklärende Beschreibung der Landformen* (Leipzig, 1912), p. 259.

by persistent upheaval, are enabled to deepen their valleys as rapidly as the region is upheaved. In this stage (if the valley sides are still kept essentially graded from stream bank to ridge crest), the ridges will be lowered as fast as the valleys are deepened, and both the absolute altitude of the crests, which is then at its maximum, and their local relief will remain constant; and the ridge altitudes will still be as nearly alike as the streams are uniformly spaced. (The deductive analysis which leads to this conclusion is not presented. In its absence, it is difficult to understand how the larger streams can be impelled to more rapid downward erosion than before by the continued and uniform upheaval of the mountain region, without being thrown out of their graded condition and therefore incising rock-walled gorges in the bottom of their previously graded valleys; and in that case the control of ridge-crest height by valley depth must be imperfect. Perhaps a postulate of non-uniform upheaval would lessen this difficulty.)

When upheaval at last ceases, it is supposed that for a time the valleys will still continue to be degraded by downward erosion. In this stage the ridges, in so far as their side slopes are graded with respect to the valley bottoms, will for a time retain sharp crests, and their local relief will remain unchanged although their absolute altitude now begins to decrease. (It is difficult to accept this deduction. If the streams and the ridge slopes were essentially graded during the latest phases of upheaval, the valleys could not be deepened significantly until the detrital load that had to be swept along them by the streams was decreased; and such decrease would not ensue until the ridge slopes were reduced to a gentler declivity than before, and such a reduction of declivity would entail a reduction of ridge-crest relief over valley bottom.) At a still later stage, the land mass remaining stationary, the streams will further diminish their fall and become more perfectly graded. The valley floors will then be opened and widened, the graded slopes of the ridges will be worn to a gentler declivity, and the ridge crests will be rounded. The ridges will then decrease in local relief as well as in absolute altitude. Finally downward erosion ceases, the valleys are still further broadened, the rounded ridges are worn down to broad swells, and the swells are eventually almost obliter-

ated. (It is noteworthy that, in spite of Passarge's dictum as to the futility of deducing the late stages of an erosion cycle under the assumption of unchanging climate—because in his belief climate changes repeatedly during a period so long as a cycle of hard-rock erosion—Penck nevertheless tacitly postulates a uniform climate. It would be better to say regarding the old age of a cycle that downward erosion is more and more retarded than that it ceases, for there must still be some downward erosion as long as the streams have to lower their grades in order to adjust them to the decreasing discharge of waste from the lowering swells. Gilbert has shown that, for a far inland region, such as the plains of central Colorado, not only the valley floors but the whole surface may be lowered hundreds of feet as a result of continued but very slow downward erosion by the streams even after the stage of peneplanation is reached.)

The most significant stage of this ideal cycle is held to be the intermediate one in which the sharp ridge crests maintain a constant absolute altitude as well as a constant relief, in consequence of a balance having been struck between the rate of upheaval and the rate of deepening the larger valleys; but the duration of this stage is shorter than that of the sharpened crests, which persist in the preceding stages while crest altitude is increasing, as well as in the following one while it is decreasing. For these three stages, in which the sharpness of ridge crests is maintained, my term "mature" as originally defined, seems appropriate, in view of the maximum strength and variety of relief then acquired by the mountain mass with its steep but graded slopes; but Penck discards the German equivalent, *reif*, of that term which he had previously used, and speaks in paraphrase, "von einem ausgewachsenen Gebirge mit dem Schneidenstadium der Entwickelung, welches ein Gegenstück zum Schluchtstadium der Täler darstellt, aber von kürzerer Dauer ist." (That the mature stage of sharpened ridges with graded slopes down to the streams should be of shorter duration than the young stage of flat interstream uplands and rock-walled gorges does not seem to be proved.)

Second and third ideal cycles.—In the second ideal cycle, strong upheaval of short duration, and hence of moderate total amount, is

postulated. Here the flat interstream uplands cannot be reduced to sharp crests because they are not lifted high enough to be consumed by the wasting of the valley-side slopes while the slopes are still steep; the uplands are therefore transformed into rounded ridges, and after upheaval ceases the rounded ridges are slowly worn down. Although the sharp-ridge stages of the first ideal cycle are wanting in this second ideal cycle, the earlier and the later stages of both cycles are much alike. In the third ideal cycles, a slow upheaval is postulated: here the valleys are deepened about as fast as the land is raised, they are widened faster than they are deepened, the flat interstream uplands are degraded almost as fast as they are raised, and sharp forms of strong relief are therefore unattainable however long upheaval continues. (It may be here noted that valleys which, either by reason of slow upheaval or of weak rocks, are opened with graded slopes as fast as they are deepened, may be described as "born mature"; also that a region which represents the third ideal cycle may be described as "old from birth." Furthermore, the late stage of Penck's third cycle will be very similar to the late stages not only of his second and first cycles, but also of a cycle of erosion introduced by an upheaval so rapid that little erosion is accomplished while it is taking place. The chief difference between the late stages of these four ideal cycles would seem to be that the streams would be best adjusted to weak structures by the process of river capture in the last mentioned cycle of very rapid upheaval, and least adjusted in Penck's third cycle of very slow uplift; this being for the reason that the more rapid the upheaval, the better the opportunity for large streams to cut down their valleys to a greater depth than that of small-stream valleys.)

Uncertain application of the first ideal cycle to the Alps.—Although no separate examples of mountain forms are adduced in illustration of the second and third ideal cycles, it is pointed out that in a single mountain system, such as the Alps, these two cycles may perhaps find exemplification near the mountain margin, where upheaval was presumably slow and small, and where the ridges are usually rounded. At the same time the first ideal cycle is thought to apply to the center of the Alpine system, where upheaval

has been stronger and greater, and where the mountain crests are sharpest; but the stage of the first cycle to which the preglacial central Alps correspond is not specified. In any event, the initial conditions of the first cycle must be modified before they can represent the case of the Alps by assuming, not an antecedent lowland, but a region of subdued mountain forms, which Penck finds reason to believe had been developed there in an early cycle of erosion before the uplift by which the cycle of preglacial carving was introduced; this early cycle of erosion—or a still earlier one—having destroyed the great inequalities of altitude due to the huge Alpine overthrusts.

It must, however, be a difficult matter to determine whether the conditions of uplift and erosion postulated in Pencks' first ideal cycle really represent those under which the Alps gained their preglacial forms; for apart from the highly specialized relation of unrelated factors which, as pointed out above, is necessary for the persistence of graded streams and of graded ridge slopes during progressive upheaval, there remains the large uncertainty as to whether those parts of the high Alps in which no trace of earlier-cycle forms now survive may not have gained a considerably greater altitude than now at an early stage of the preglacial cycle in virtue of a rapid upheaval—such an upheaval, for example, as that which, acting on a much larger scale, gave the Himalayas their towering heights of today; and also an uncertainty as to whether the rough equality of present Alpine altitudes may not be competently explained chiefly by erosion after upheaval had ceased, as Penck formerly supposed, rather than by a delicate balance of erosion and upheaval as he now suggests. The idea of a constancy of height being imposed on mountain crests by a balance between upheaval and degradation is a beautiful one, and the ingenuity of the analysis by which the idea is carried out is not to be questioned, but its application to Alpine summits does not seem fully assured. As already noted, the region of the Alps was not a lowland at the time preceding the upheaval by which the preglacial cycle was introduced, but as Penck himself shows, a region of subdued mountains. The upheaval was not broadly uniform, as the scheme of the first ideal cycle tacitly assumes, but, as Penck himself again

shows, was significantly greater in certain areas than in others. He indeed suggests that certain longitudinal valleys of today represent belts of smaller and slower upheaval than the areas of lofty and sharp peaks; hence the generalized surface of upheaval, instead of being a single very broad arch from south to north, appears to have been an undulating arch; and, if that were the case, a moderate increase in one of the convexities, as the result of a locally strengthened and accelerated but relatively brief upheaval, might produce the great initial altitudes above suggested. It may be noted in this connection that Sölch, professor of geography at Innsbruck, has recently pointed out certain difficulties that stand in the way of accepting Penck's views.[1]

Let it be added that it is physiographically immaterial to which one of the three sharp-crested stages in Penck's first ideal cycle the preglacial Alps correspond; all three stages would look alike. Similarly, it is physiographically immaterial whether young mountains with flat interstream uplands and subdued mountains with rounded crests are to be explained by his first or his second ideal cycle, which in the early and late stages develop similar forms. Again, it is physiographically immaterial whether old mountains—that is, masses of deformed structure, once lofty but now reduced to undulating lowlands—are to be explained by his first, second, or third ideal cycle, or by a cycle introduced by a very rapid uplift, except in so far as a prevailing adjustment of drainage to weak structures would suggest the operation of a rapid uplift, or of the first instead of the third of Penck's cycles, as noted above.

PART II. THE SCHEME OF THE EROSION CYCLE

Physiographic principles of the erosion cycle.—In order more fully to appreciate the novelty of Penck's discussion, a brief review may be made of the leading physiographic principles that are associated with the scheme of the erosion cycle. One of these principles is that highlands and mountains in existence today are not necessarily the unconsumed residuals of a single primitive upheaval, but that they may be and in many cases are the residuals

[1] "Grundfragen der Landformung in den nordöstlichen Alpen," *Geogr. Annalen*, Vol. IV (Stockholm, 1922), pp. 147–93; see p. 187.

of a renewed upheaval which took place after a more or less complete degradation of the region as prompted by an earlier upheaval. Early recognition of this principle is found in the writings of Ramsay, Powell, and others. Nearly eighty years ago, Ramsay clearly explained the possibility that the hills of South Wales might result from the incision of valleys in an uplifted plain of marine denudation, which had been abraded across a mountainous area of earlier deformation and uplift,[1] and the latest physiographic studies of this region give good reason for thinking that the old master was right, at the same time amplifying his view by showing that the present hill-top levels indicate the occurrence of two plains of marine origin; an inner and higher plain partly consumed by the undercutting of an outer and lower one, the two being separated by a scarp which, although still recognizable, is now like the two plains well dissected.[2]

Twenty years later Powell, when he visited the Rocky Mountains of Colorado in 1867 with a party of students, came upon a similar principle, namely, that the mountains of today may be in a second cycle of erosion after almost complete obliteration of more primitive mountains by subaerial degradation in an earlier cycle; but his only mention of this discovery s in a brief statement published some years later, where it did not attract attention.[3] In the same later volume he first announced an explanation of the Basin ranges which was later very generally accepted, his idea being that before the upheaval of the existing ranges their region was "a comparatively low plain, constituting a general base level of erosion to which that region had been denuded in Mesozoic and early Tertiary time when it was an area of dry land; for I think that from the known facts we may reasonably infer that the Basin ranges, though composed of Paleozoic and Eozoic rocks, are as mountains of very late upheaval.[4] That was a very sagacious utterance for its time.

[1] A. C. Ramsay, "Denudation of South Wales," *Mem. Geol. Surv. Great Britain*, Vol. I (1846), p. 327.

[2] The only published statement of these later studies, made by O. T. Jones, is contained in a rather inaccessible volume: *Souvenir of the Aberystwyth Conference, National Union of Teachers, 1911*. Edited by John Ballinger. Published by the National Union of Teachers, Bolton House, Russell Square, London, 1911.

[3] *Geology of . . . . the Uinta Mountains, Washington* (1876), p. 27.

[4] *Ibid.*, p. 32.

Embodied in the first principle of the cycle—that the erosion of the earth's surface has been accomplished in successive intervals of time marked off by movements of upheaval—is a closely associated second principle to the effect that, during the epochs of rest between the movements, the destructive action of the sea waves on the shore line, or of weather and streams on the entire extent of an uplifted region, may reduce it to a low and nearly featureless surface; a plain of marine abrasion in the one case, a plain of subaerial degradation in the other. An extension of this second principle allows it to include, besides the two just named, other kinds of destructive processes: weather and glaciers, weather and wind (with occasional rain), weather and solution; the latter process finds application particularly in limestone regions and has been worked out chiefly by European observers in the Karst region east of the Adriatic. It may be noted in passing that the reduction of a forest-covered highland to a lowland by the ordinary agencies of subaerial degradation is chiefly accomplished, after the streams have cut their valleys down to grade and after the valley sides have become covered with a sheet of locally weathered soil, by the very slow process of soil creep, attention to which was first directed in this country, as far as I have read, by Lesley in his admirable little book on "Coal and its Topography" (1856).

The most striking illustrations of these two principles are found in regions which, during an earlier cycle of erosion, had reached peneplanation or extensive abrasion, and which are now, after a later uplift of simple character, in so early a stage of renewed dissection as to preserve in their unconsumed uplands little modified remnants of their former lowlands of small relief. Many examples of this kind are now known; indeed a good number of the greater mountain ranges of the world seem to be in a later cycle of erosion than the one introduced by their deformation, and to have suffered far advanced erosion in the cycle preceding the one now current. On the other hand, many other regions show that the movement or deformation by which a later cycle is introduced may interrupt an earlier cycle at any stage of its advance; and also that the interrupting deformation may be of any kind, small or great, simple or complex, slow or rapid, brief or long-enduring. Finally, it

must be understood that while the existence of various slightly dissected plateaus and mountainous highlands proves that in such cases the movement of upheaval was rapid compared to the general processes of subaerial degradation, the occasional occurrence of valleys transecting upheaved masses proves that the antecedent rivers which eroded such valleys were competent to cut down their channels about as fast as the transected mass was upheaved. Hence while an elementary conception of the cycle implies that erosion was chiefly accomplished after upheaval ceased, a more matured conception recognizes that much erosion may take place while upheaval is in progress. The elementary conception may, however, be nearly realized in regions of resistant rocks, quick uplift, and weak destructive agencies; the more elaborate conception may be most fully realized in regions of weak rocks, slow uplift, and strong destructive agencies.

It thus came to be more and more generally recognized that every eroding land area exhibits in its actual form the present stage of a succession of changing forms that began when the area was uplifted and exposed to erosion and that will continue, if no disturbance takes place, until it shall be worn down to a featureless lowland. With the recognition of this succession for actual land areas came its generalization for imagined land areas. Thus concepts of typical cycles of erosion took their place along with concepts of typical rivers, volcanoes, and so on. Progress since then has been made, on the one hand, by inferring past and future changes of many actual land areas, and on the other, by enlarging the number of imagined cycles and elaborating the discussion of their succession of changes.

A third principle of the cycle has been thus established, namely, that a systematic sequence of forms is developed during its progress, the sequence varying according to the structure of the mass that is to be eroded and to the nature of the processes by which the erosion is done. The discussion of each structural unit or entity should, therefore, be carried through separately. The structure of such an entity may be uniform or varied, simple or complex, resistant or weak; the processes of erosion may be, as above noted, weather and rivers, weather and glaciers, weather and wind, weather and

solution (in limestone areas), or weather and waves; and some of these various processes may interact in the same region. This third principle is closely associated with a fourth, namely, that at any stage in the systematic advance of a cycle of erosion, the various elements of form then developed are reasonably associated with one another in a manner appropriate to the structures and processes concerned; and herein lies the chief value of the scheme of the cycle of erosion in the explanatory description of land forms. It advances land physiography from an empirical study of unrelated facts to a rational, evolutionary, genetic study of closely correlated facts. The contributions to the establishment of these two principles have been so numerous that it is impossible to list them here; but one of the earliest and most helpful is to be found in a chapter on the erosion of Alpine valleys in Heim's famous *Untersuchungen über den Mechanismus der Gebirgsbildung*,[1] a work which marked at its time a great advance in the study of the erosional development of valleys during the progress of mountain carving, and which may be appropriately cited here in order, as will be more fully shown below, to measure the great additional advance that has been made in that most difficult and most important of all physiographic problems during the following half century. It may be further noted that my own share in developing the scheme of the erosion cycle has been chiefly in the way of systematizing the ideas brought forward by others.

The terminology of the erosion cycle.—A section may be given to some items of terminology in the scheme of the erosion cycle. The use of the word, cycle, in this connection is my own suggestion. A complete cycle denotes the lapse of time between the initiation of the uplift of a land mass by any kind of deformation and its ultimate degradation. Two ordinary words—interrupt, meaning the closing of a cycle at any stage of its progress by a movement of the land mass, and introduce, meaning the opening of a new cycle by such movement—are not technical terms, but it is convenient to employ them systematically in the sense just indicated. They have been so used above. The disturbance of the progress of a

[1] Vol. I, pp. 293–301, Basel, 1871.

cycle by volcanic eruption or by changes of climate (other than the normal decrease of precipitation and increase of temperature that accompany the degradation of a highland) I have suggested should be called accidents, in order to distinguish them from interruptions due to crustal movements.

The three terms, initial, sequential, and ultimate, referring to the opening, the prosecution, and the ending of a complete cycle of erosion, are due to Gulliver. The application of words taken from the organic cycle of life to indicate stages in the inorganic cycle of erosion was first made—not poetically, but physiographically—as far as I know, by Chamberlin and Salisbury in 1885, when they described a district with narrow valleys as young, and one with open valleys as old;[1] I modified this suggestion by calling a district with open valleys mature, and reserving old for a district in which the inter-valley hills have been almost worn away; but always with the understanding that these organic terms should serve only to suggest, in the briefest possible manner, the general surface features of a structural entity: they must be supplemented by many details in a full description. Even when their application is limited to a structural entity, it is important to recognize that its weaker rocks are more rapidly eroded than its stronger rocks, and hence that belts of weak strata may already be old when belts of resistant rocks are only mature, as is repeatedly the case in the Pennsylvania Alleghenies.

One of my later proposals was that an almost worn-down surface should be called a peneplain; that new word being invented in order to avoid the term, plain of erosion, which excited opposition as demanding too long a stationary condition of the earth's crust for its production. Conoplain has been proposed by Ogilvie to name a surface of subaerial degradation that declines gently in all directions from a central area.[2] Monadnock, following the analogy of meander—the name of a particular serpentine river now commonly used to indicate the curves that similar rivers follow—is

[1] "The Driftless Area of the Upper Mississippi," *Sixth Ann. Rept. U.S. Geol. Surv.*, pp. 205–322.

[2] *Amer. Geol.*, Vol. XXXVI (1905).

the name of a particular residual mountain that has come to be used for such mountains in general.

It may be added that young, mature, and old seem to be best used in connection with features that persist, but with appropriate changes, all through a cycle, such as forms of relief, rivers, and shore lines; and not with features of shorter endurance, like lakes and waterfalls, which are characteristic only of a part of a cycle.

As to terms for rivers and valleys, "antecedent," "consequent," and "superimposed" are due to Powell; the last was shortened to "superposed" by McGee. "Subsequent," which Jukes used in a descriptive sense, I have used similarly in a restricted and technical sense for streams that have grown headward by retrogressive erosion along belts of weak structure, and also for streams which, having been thus developed in one cycle, persist in the same courses in a following cycle. It may be noted that, while consequent rivers and valleys commonly exhibit a bilateral symmetry, subsequent rivers and valleys as commonly do not; also that subsequent streams are very commonly found in pairs on opposite sides of a consequent stream, thus constituting characteristic elements of its bilateral symmetry. McGee's "autogenetic" I have replaced by "insequent," in order to bring it into the sequential group of terms, to which I later added "obsequent" and "resequent."

It is worth noting that the terms of the sequential series may be used for other features than streams and valleys. Thus an anticlinal arch may be called a consequent ridge as long as it retains its axial eminence. When it is breached along the axis by the excavation of weak strata underlying a hard cover, so that the initially single crest is divided by a subsequent anticlinal valley into two lateral crests, they may be called subsequent ridges; their outer slopes are still consequent slopes; their inner slopes are obsequent slopes. If the continuation of erosion reveals along the axis of the breached anticline another anticlinal arch of hard strata, it will gain relief as the first-developed anticlinal subsequent valley is divided into two lateral or monoclinal subsequent valleys; the anticlinal ridge between them is then a resequent ridge. The Appalachian mountains of Pennsylvania and Virginia give abundant

examples of these various kinds of forms. Consequent, obsequent, and resequent may also be advantageously used in the explanatory description of scarps on faulted structures, with particular relation to later cycles of erosion than the one introduced by the faulting.[1] The failure to distinguish between consequent fault scarps and resequent or obsequent fault-line scarps has sometimes led to errors as serious as those resulting from the failure to recognize subsequent valleys as constituting a class by themselves, altogether unlike in origin to antecedent, consequent, and superimposed valleys. It is significant that Powell's terms, anaclinal, cataclinal, etc., which he invented to express empirical relations between streams and structures, have been little used as compared to the terms of the sequential series.[2] A preference is thus implied for terms that express genetic relations.

The term grade, used to describe the smoothed courses of mature and old streams that are neither wearing down nor building up their beds, is due to an oral suggestion by Gilbert. It stands nicely between the long familiar term, degrade, and Salisbury's newer term, aggrade; and it may be as well applied to sheets of waste on soil-covered hill sides, as to streams of water in smooth valley bottoms. The same term also serves properly in connection

[1] "Nomenclature of Surface Forms on Faulted Structures," *Bull. Geol. Soc. Amer.*, Vol. XXIV (1913), pp. 187–216.

[2] A number of elaborate explanatory terms have been suggested without reaching general acceptance. Löwl's terms, symptygmatisch, bikataklastisch, pseudotektonisch, etc., for the descriptions of valleys (*Ueber Talbidung*, Prague, 1884) have not come into use. Penck's terms, homogenetisch and homoplastisch, for forms of similar origin and of similar shape ("Die Geomorphologie als genetische wissenschaft," *Ber. 6ten Internat. Geogr. Kongr.*, London, 1895), are rarely encountered. Passarge's mono dynamische and polydynamische Einzelformen ("Physiologische Morphologie," *Mitt. Geogr. Ges.*, Vol. XXVI, Hamburg, 1912) and Falconer's exogenetic positive or negative forms and endogenetic negative tangential fracture landscape forms ("Land Forms and Landscapes," *Scot. Geogr. Mag.*, Vol. XXXI, 1915; see pp. 394–401) are seldom if ever quoted by others than their authors. Among my own proposals that have not been later used even by myself are compound, complex, and composite, as names for rivers of different origins ("Rivers and Valleys of Pennsylvania," *Nat. Geogr. Mag.*, Vol. I [1889], 183–253; see p. 219). Whether morvan ("Relation of Geography to Geology," *Bull. Geol. Soc. Amer.*, Vol. XXIII [1912], pp. 93–124; see pp. 112–18; also: "A Geographical Pilgrimage from Ireland to Italy," *Ann. Assoc. Amer. Geogrs.*, II [1913], pp. 73–100; see pp. 89–92.) will share a similar fate, or whether it will be adopted like monadnock remains to be seen.

with mature and old shoreline features; but here, as the action of waves is essentially in a horizontal plane, degrade and aggrade should be replaced by retrograde and prograde. The various river terms may be modified by such adjectives as revived or rejuvenated —Heim long ago used the word "Neubelebung"—to suggest idea that a recent upheaval has brought about a youthful stage in a current cycle after a more advanced stage in a previous cycle. Philippson introduced the important idea that revival of stream erosion in the upper part of a river system may be brought about as well by a down-flexing or down-faulting of the lower part of the system as by a general uplift, for thereby the headwaters will be enabled to incise their former valley floors.

Philippson also developed the idea of migrating divides, and the resulting rearrangement of water courses, as in the case of a higher-level stream that is tapped by the headward growth of a lower-level stream at what I have called the "elbow of capture" and thus divided into two parts, the upper part being diverted and the lower part beheaded. As the lower-level stream head approaches the elbow of capture, the divide between them creeps toward the higher-level stream; at the time of capture the divide leaps around the basin of the diverted stream; then as a rule, again creeping slowly, it still further beheads the beheaded stream: a short stream is thus developed between the retreating head of the beheaded stream and the neighborhood of the elbow of capture; as it flows in a back-handed direction it may be called an inverted stream.

Captures of this kind are largely the work of subsequent streams: they may be described as eventual, imminent, recent, and long-past or remote. As they are accomplished, a drainage system departs more and more from its initial consequent pattern and becomes more and more fitted or adjusted to belts of weak structure, and at the same time the surviving ridges and divides become adjusted to belts of resistant structure. The reduced volume of a beheaded stream cannot develop meanders of the same size as those which it followed, with larger volume, before its beheading and by which its valley may have been given an incised meandering pattern; hence, as the reduced meanders are too small to fit their valley curves, they may be called underfit. Conversely, the capturing stream, being

rapidly much increased in volume at the time of capture, may for a time be overfit in relation to its valley pattern. It is believed that underfit rivers may also result from climatic change, as well as from a reduction of stream volume (during unchanged climate) by loss of surface water to underflow in the flood-plain deposits of mature valleys, according to what I have called Lehmann's principle, after its discoverer.[1] Streams that, by reason of uplift, have lengthened their courses across an emerged sea floor, were called extended by Tarr; if extended streams, formerly separate, are led to join in a single trunk, I have called them engrafted; if the branches of a trunk river are separated by the submergence of their main valley, they may be called betrunked or dismembered.

It is manifest that many of these terms may be used in any rational method of physiographic description, but they are peculiarly helpful in the explanatory method based on the scheme of the erosion cycle because the features that they designate are so closely related to one or another of its successive stages. Thus, while consequent streams are defined by the initial slopes of a land surface, and are as a result established at the beginning of a cycle, subsequent streams are not well developed till a mature stage is reached, and obsequent and resequent streams are of later development than subsequents. Similarly, grade is a condition that characterizes the stages of maturity and old age; river captures, especially the captures of consequent headwaters by growing subsequent streams, occur chiefly in the stage of maturity. The adjustment of streams and ridges to belts of weak and resistant structures is also a characteristic of the mature and later stages; and so on.

Gradual development of the cycle scheme.—A correspondent has called my attention to an aphorism of Hegel's, to the effect that a new truth has a short period of victory between an earlier time when it is opposed as a heresy and a later time when it is passed by as a commonplace. Such is truly the case with the general principle that subaerial degradation may in time reduce any mountainous highland to a nearly featureless lowland, on which the scheme of

[1] "Meandering Valleys and Underfit Rivers," *Ann. Assoc. Amer. Geogrs.*, Vol. III (1914), pp. 3–28.

the normal cycle of erosion is founded. This principle was regarded as a dangerous extravagance less than forty years ago; it is usually taken as a matter of course today. But as regards cycles of erosion in which various other processes than "normal" erosion by weather and streams are involved, there is still so much to be learned that they have not yet become commonplace matters. They are still in need of fuller discussion; indeed various refinements are undoubtedly still to be made regarding certain aspects of the ordinary cycle of normal erosion; and the gradual advances by which its present development has been reached ought to prove that even this simplest of all the special forms of the cycle scheme has not yet reached the perfection of an infallible finality. Campbell's discussion of the effects of a moderate tilting on the shifting of divides and the rearrangement of stream courses[1] is a good example of the kind of investigation that different elements and possibilities in the normal cycle need. Careful study should still be given to the manner in which differences of climate affect the work of weather and water and the extent to which surface forms are thereby influenced: the good beginning in such a study made by Passarge for cold, temperate-humid, temperate-subhumid, temperate-arid, and torrid zones in the third volume of his *Landschaftskunde* (Hamburg, 1920) would have a larger value if it had not been limited by his rejection of soil-creep on forested slopes as an effective agency of degradation, as I propose to show in a review to be published elsewhere. A somewhat similar study by Sapper, *Geologischer Bau und Landschaftsbild* (Brunswick, 1917), is less satisfactory because no effort was there made to select really comparable land forms—that is, land forms of similar structure and in a similar stage of erosion—from the different zones.

Among the land forms that vary with differences of climate, to which my own attention was directed during a Pacific voyage in 1914, are ridge crests in relatively homogeneous rocks. In temperate climates of moderate rainfall, ridges are usually forest-covered and their crests acquire a well-rounded or convex cross-profile when the valleys between them are well opened; and even

[1] "Drainage Modifications and Their Interpretation," *Jour. Geol.*, Vol. IV (1896), pp. 567–81, 651–78.

in the fine-textured forms of bad lands, the divides are delicately rounded, instead of being acutely sharp, as Gilbert was led to expect they should be in his study of land sculpture by running water and the law of divides.[1] The rounding of such crests appears to be due to soil-creep, as he later showed.[2] But in torrid lands of rapid weathering and heavy rainfall, the ridges that rise between broadly opened valleys are so extraordinarily sharp that, in proportion to their breadth, they realize the knife-edge acuteness which Gilbert believed ought to result from degradation by running water; and the meaning of their sharpness appears to be that, under the extra-heavy rainfall they receive, they really are shaped chiefly by running water rather than by soil-creep, in spite of the rapidity with which soil is there produced. These broad and sharply divided valleys resemble in a surprising degree certain broadly opened and sharply separated troughs of deglaciated mountains, except that their cross-profiles have no "shoulder" between the higher weathered slopes and the lower wall of glacial scouring.

As to the marine cycle, Gulliver's general account of "Shore-line Topography"[3] has been greatly extended in Johnson's *Shore Processes and Shore Line Development* (New York, 1919). An item that characterizes the mature and later stages of this cycle to which attention has seldom been called is the then frequent occurrence of cliffs of decreasing height; that is, cliffs which have been cut back so far that they now stand behind the former summit of a hill or former crest of a ridge, so that the more they are abraded the lower they become, until the valley beyond them is reached. In regard to the cycle of glacial erosion, valiant efforts have been made by various observers in the Alps to detect the effects of successive epochs of decreasing glaciation, not only in form of trough-valleys, but also in the pattern of valley-head cirques. If these efforts prove successful they will give an increasing delicacy to the description of mountain forms. The solution cycle, not formulated until after the normal cycle had become familiar, has greatly facilitated the description of Karst lands.

[1] *Geology of the Henry Mountains, Washington* (1877), p. 122.

[2] "The Convexity of Hilltops," *Jour. Geol.*, Vol. XVII (1909) pp. 344–50.

[3] *Proc. Amer. Acad. Acts and Sci.*, Vol. XXXIV (1899), pp. 149–258.

The arid cycle is least developed; its theoretical aspects have been carried far beyond their confirmation by observation; not that observation in deserts is wanting, but that the observers there have usually failed to test the correctness of the expectations to which the deductive discussion of this special cycle have led.[1] Walther's studies of deserts are as a rule more concerned with the actual processes there at work and the forms that they immediately produce rather than with the place of such processes and forms in the whole sequence of inferred forms that constitutes a complete cycle of arid erosion. Certain phases of the arid cycle have, however, been admirably analyzed with respect to actual features in the desert region of the southwestern United States by Lawson[2] and Bryan.[3] In all its aspects, the scheme of the erosion cycle has grown by degrees, sometimes slowly, sometimes rapidly; and its growth is still going on, partly by the correction, partly by the modification and extension of earlier ideas.

Reception of the scheme of the erosion cycle.—With many of the older physiographers and geologists in the United States today, whose individual development in their science has been contemporaneous with the growth and establishment of the scheme of the cycle of erosion, its use has been an every day affair, and its advance has been a part of their own progress; but they have often made more use of its principles than of its terminology. Among the younger ones, the scheme has been very largely accepted, ready made, from their seniors. But a few reservations are here needed: for example, the term subsequent, defined as above, has been seldom employed, in spite of the very frequent occurrence of subsequent rivers and valleys in regions of deformed strata; it has been replaced by paraphrases. Other terms, such as obsequent and resequent,

[1] Since writing the statement above, a paper by E. Kaiser, of Munich, on "Morphogenetische Ergebnisse auf Reisen während des Krieges in Südwestafrika" (Verh. 20, *Deutschen Geographentages* [Leipzig, 1921], pp. 159–75) has been received, in which it is said that the observed forms of the coastal desert near Lüderitz Bay confirm certain of the deduced forms of the arid cycle (see p. 175).

[2] "The Epigene Profiles of the Desert," *Cal. Univ. Dept. Geol. Bull.*, Vol. IX (1915), pp. 23–48.

[3] "Erosion and Sedimentation in the Papago Country, Arizona," *U.S. Geol. Surv., Bull. 730 B*, 1922.

have been rarely used, apparently because few physiographers care to carry their analyses so far into detail as the use of these terms implies.

In Great Britain the scheme of the erosion cycle has not been actively cultivated, although its leading principles appear to be more or less passively accepted there. In France the principles of the scheme were largely recognized by de la Nöe and de Margerie in their notable work, *Les Formes du Terrain* (Paris, 1888), and the developed scheme was cordially adopted by de Lapparent and given effective publicity in his *Leçons de Géographie physique* (Paris, 1896); it has since then been practically applied in a number of essays, but the devotion of most French geographers to the historical aspects of their science seems to have caused them to give only a secondary attention to physical geography, the scheme of the cycle of erosion included.

In Germany a number of geographers, including Penck,[1] Rühl,[2] and Braun,[3] have accepted the scheme more or less fully, but certain others, especially Hettner[4] and Passarge,[5] have rejected it on various grounds. Some of the objections to it may be noted.

Objections to the scheme of the cycle.—Various objections have been made to the terminology of the scheme. In spite of the not infrequent use of the German word for cycle (Zyklus) in such a phrase as a cycle or course of lectures, in which the conclusion of the last lecture need have no relation to the introduction to the first, the phrase "cycle of erosion" has nevertheless been objected to because the initial form is not returned to in the ultimate form. However, if insistence be made on that point, it may be answered that a good number of cycles do begin and end with very similar forms. Such is the case with plains and plateaus; and also singularly enough

[1] See his chapter in Scobel's *Handbuch*, referred to above.

[2] "Eine neue Methode auf dem Gebiet der Geomorphologie," *Fortschr. naturwiss. Forschung*, VI (1912), pp. 67–130.

[3] *Grundzüge der Physiogeographie*, Leipzig, 1st ed., 1911; 2d ed., 1915–17. This book is a modified translation of my *Physical Geography*.

[4] In addition to various essays in the *Geographische Zeitschrift*, see *Die Oberflächenformen des Festlandes*, Leipzig, 1921.

[5] "Die Grundlagen der Landschaftskunde," *Die Oberflächengestaltung der Erde*, Vol. III, Hamburg, 1919.

with the many second-cycle mountain ranges which are produced by the uplift and dissection of a peneplain that had been worn down on a mountain mass of disordered structure in an earlier cycle.

Objection has also been made by German geographers to the use of the organic terms, young, mature, and old, to represent successive phases of an erosion cycle, because they insist on interpreting them to mean age in time-measure, instead of stage in development. Yet if two geologists, habituated to use young and old as time-measures in relation to geological formations, were walking across country, and one of them said: "See that young oak," and a moment later added: "Look at this old mushroom," neither of them would for a moment imagine the oak to have lived a shorter time than the mushroom. The young oak might, indeed, be hundreds of times longer-lived in time-measure than the old mushroom. Hence if the organic terms are used in their developmental sense, there should be no difficulty in understanding what is meant by them.

One of the most common grounds for objecting to the scheme of the erosion cycle seems to be a general misunderstanding of its object. Several European geographers have misconceived it as a rigid scheme, to which the varied facts of nature must be forced to conform, instead of as an elastic scheme, readily modified to conform to the varied facts of nature. It has been misunderstood as always demanding a rapid or sudden upheaval, so rapid or sudden that practically no erosion could take place until the upheaval was accomplished. Yet slow upheaval movement with accompanying erosion is manifestly as easily postulated as rapid upheaval. Others seem to have supposed the scheme to present final and infallable conclusions; and on discovering an error or omission, they feel that the scheme must be discarded in its entirety. In my own case, at least, the scheme has been a growth, and its growth is by no means completed. Moreover, however many modifications, improvements, and extensions the scheme may now or later receive, it should be remembered that they are all based upon the valid principles of the scheme already established, and that but for the previous establishment of those principles the improvements of the scheme could not be made. Such modifications and extensions

are like strengthened or reset rungs or newly added upper rungs in a physiographic ladder, on the lower rungs of which a good measure of ascent has already been made above the empirical level of the science fifty years ago. It is not to be questioned that various special cycles have yet to be worked out in order to develop form-sequences appropriate to peculiar structures and processes; and it is greatly to be desired that systematic studies of this kind should be combined with the observational studies of trained geographers in regions of unlike climates. And now after this long detour away from the Alps, return may be made there in order to show that Penck's explanation of the similar summit altitudes involves the elaboration of precisely such a special sequence of forms as contributes to the fuller development of the cycle scheme; but his study unfortunately includes an element of destructive criticism to which attention must also be called.

PART III. PENCK'S CRITICISMS OF EARLIER STUDIES

Progress in Alpine physiography.—It is profitable to read in connection with Penck's *Gipfelflur der Alpen* Heim's chapter on the denudation of mountains which, already referred to as published in his *Mechanismus der Gebirgsbildung* half a century ago, marked the farthest advance reached at that time in the most difficult problem of land physiography. It was then tacitly assumed that the present cycle of Alpine erosion had been introduced by the great crushing which produced the greatly deformed Alpine structures; the possibility of successive more or less complete cycles of erosion, introduced by simple uplift and following after an advanced stage of the earlier cycle introduced by the crushing, was not thought of. Nor was the scheme of one-cycle erosion then carried to its legitimate end of peneplanation; if such a possibility was imagined it was probably dismissed as an extravagance. Furthermore, the important share that glacial erosion has taken in the sculpture of the Alps had not then been learned.

Many are the modifications of those early views that have since been accepted. It is now recognized that the Alps are no longer in their first cycle of erosion, but that the present cycle was preceded by another—whether that one was the first need not be

considered here—in which their enormous overthrusts were enormously eroded; and that the present eminence of the Alps is not a residual of their upheaval at the time of lateral compression, but of a much later and more moderate arching—an undulating arching as Penck now interprets it—by a relatively simple uplift. Moreover, the great work of glacial erosion is now fairly well understood and carefully allowed for, the best study of this great problem being in Penck and Brückner's masterly work, "Die Alpen im Eiszeitalter"; and the immediately preglacial forms of the mountains are believed on valid grounds to have been prevailingly sharp-crested ridges. Finally, instead of assuming a single rapid upheaval as having introduced the present cycle of erosion, Penck proposes several alternative postulates regarding the rate and duration of upheaval and examines their consequences, with the result of selecting the postulate of long-continued upheaval at a moderate rate as providing the best counterpart of the movement to which the present Alps owe their elevation, and of ascribing their fairly uniform summit altitudes to a balance between upheaval and erosion.

Whether the deductions from the postulate of long-continued upheaval are accepted as valid or not, the general sequence of forms that is traced out is a beautiful one. First, both the altitude and the relief of the young mountains are increasing, the increase of altitude, but not of relief, being as fast as the upheaval of the mountain mass; then while the ridges are sharpened, their altitude continues to increase, but now a little more slowly than the rate of upheaval, and the relief is held at a constant value; next, continued upheaval being balanced by degradation in full maturity, altitude reaches and is maintained at a constant maximum, while relief stands unchanged; later, upheaval ceases and altitude is slowly decreased, although for a time the ridges are still sharp and their relief is still unchanged; finally, the sharp ridges of the quiescent mass are rounded and lowered, and thus both altitude and relief are decreased to smaller and smaller values as old age is entered upon. There is elegance as well as originality in these deductions.

Extensions and corrections of the erosion cycle.—Evidently the explicit consideration given in the *Gipflur der Alpen* to several ideal cycles of erosion, differing from each other in the rate and the dura-

tion of the upheaval by which they are introduced, is a helpful advance in systematic physiography, but the advance is not so much in the way of a correction of previous discussions as it is in their extension. Penck implies, however, on a number of his pages that his present views are corrections of earlier views. He states, for example (p. 263), that the sharp-crested preglacial Alpine ridges have been developed from pre-existent rounded ridges (dass manche Schneiden aus runden Formen hervorgegangen sind), and that such a sequence stands in opposition to a previously published scheme of a typical cycle of mountain erosion, in which a reversed sequence of forms is presented, the rounded or subdued ridges of late maturity being explained in that scheme as developed from the higher and sharper ridges of early maturity. But no real opposition occurs here, for in the earlier published statement the typical cycle of mountain erosion was supposed to begin after a previous cycle of erosion had reduced a region of deformed structure to a peneplain which, when upheaved, is dissected in such a manner that the sharp ridges of full maturity naturally enough precede the rounded and subdued ridges of later maturity in the same cycle. On the other hand, in the special case of the Alps, the sharp ridges of the preglacial stage of the present cycle were developed, as Penck clearly explains, out of the rounded ridges of an earlier cycle, which was interrupted by upheaval before peneplanation ensued. In other words, the rounded ridges were introduced, ready made, from an earlier cycle, and in that cycle they had presumably had sharp crests before they were rounded; it was in the following cycle that they were again sharpened. In this special case it is just as natural for the sharp preglacial ridges of the present Alpine cycle to have been developed out of the rounded crests of the earlier cycle, as it is for the rounded, late-mature forms of a single typical cycle which begins with an uplifted peneplain to develop out of the sharp forms of early maturity. Furthermore, had the sharp preglacial ridges of the Alps not been made still sharper by glacial erosion but had a normal climate continued instead, the ridges would have probably been somewhat rounded today in preparation for a more complete rounding in the future. Indeed, the development of rounded ridges out of sharp ridges during the progress of a typical cycle is a well

certified procedure, for it is presented as the normal sequence of change not only in my own earlier published statement of such a cycle, which Penck now criticizes, but also in his own exposition of the cycle scheme in his chapter on "Die Erdoberfläche" in the fifth edition of Scobel's *Geographisches Handbuch* (1908) above referred to; he there explained the successive stages of a cycle of erosion, with its organic terms, young, mature, and old and with its sharpened ridges afterward rounded, as a matter of common and generally accepted physiographic knowledge, for which he very properly accepted the responsibility while enjoying the profit, thus making a marked and very advantageous forward step from his treatment of the same chapter in the second edition of 1895. Flat inter-valley uplands, sharp-crested ridges, and rounded or subdued ridges are there described very explicitly as constituting the normal sequence of forms (Sc. 144). Not only so, the first ideal cycle in the "Gipfelflur" essay, in which a lowland of erosion is assumed as the antecedent form, presents the same normal sequence (264). Hence one cannot help wondering why, if it be thought necessary to assert that the special Alpine sequence stands in opposition to an earlier deduced sequence, Penck's own earlier scheme, as well as that of one of his contemporaries, is not instanced. But in reality no such assertion is necessary, because the two sequences do not stand in opposition to each other. The implication of opposition is irrelevant.

Independence of upheaval and erosion.—In certain other respects also Penck's new views are presented as corrections of view previously announced; and in all these cases, as well as one instanced above, the previous views that he selects for correction are mine. This does me entirely too much honor, for the views of mine that he selects for correction are duplicated in the published statements of his own earlier views. Had his earlier views been published merely as quotations from my writings, his present responsibility would have been less; but they were not; they were very properly published as his own views and that being the case, his own earlier statements should receive correction along with mine, if correction is really called for. But as a matter of fact correction is not called for. The views that Penck now announces are merely extensions, not corrections of earlier views that both of us have held.

Directly after his irrelevant statement that the actual sequence of forms in the Alps—rounded ridges converted into sharp-crested ridges—stands in opposition to the sequence that I have given as typical of an erosion cycle, he goes on to say that the scheme of the cycle should be treated, not as involving the action of erosion on an already upheaved mass, as Davis has done, but as involving the action of erosion during upheaval as well as afterward (pp. 263, 264). It is perfectly true that I have frequently presented the scheme of the cycle as if introduced by upheaval and continued by erosion; the reason for such presentation being that it is the simplest way of placing the general idea before beginners; but it is also true that Penck has presented the scheme in the same simple way. One of the first articles, if not the first, in which he recognized the scheme of the "Erosionszyklus," subdivides it into five stages. The first stage is the emergence of a sea bottom in the form of a gently inclined plain; in the second stage, streams incise valleys and subdivide the inclined plain into flats; in the third, the incision of the valleys is continued, their side slopes are washed down, and the flats are thereby narrowed and converted into divides, which under certain conditions may be sharp; in the fourth, valley deepening ceases and the valley floors are widened at the expense of the dividing ridges between them; and in the fifth, the ridges are worn down so low that neighboring valley floors become confluent and a plain represents the final result of the metamorphosis.[1] Not a word is said here about upheaval after the first stage, and no mention is made of valley erosion during that stage. Nine years later Penck again made a brief analysis of the erosion cycle, in which the incision of a valley is as before said to take place upon a slope (of upheaval), but not during the upheaval of the slope; and the strongest erosion is said to be instituted where the greatest surface unevenesses exist, but not during the production of the unevennesses.[2]

Interaction of upheaval and erosion.—We have therefore both presented the scheme in a simple, elementary fashion. But besides

[1] "Die Geomorphologie als genetische Wissenschaft," *Ber. 6ten Internat. Geogr. Kongr.* (1895), pp. 735–47; see p. 736.

[2] "Die Physiographie als Physiogeographie," *Geogr. Zeitschr.*, Vol. XI (1905); see pp. 9, 18.

setting forth the scheme of the cycle in this simple and elementary manner, I have quite as often extended the scheme by presenting it in a more advanced manner, as opened by upheaval and erosion acting together and completed by the continued action of erosion after upheaval ceases. Nevertheless, the interaction of upheaval and erosion has never been presented by myself or by anyone else in the beautiful manner deduced by Penck in his first ideal cycle of the "Gipfelflur" essay; and for that reason his essay should be regarded as marking an extension of the previous treatment of the cycle scheme. In order to justify the opening statement of this paragraph I desire to cite a number of passages from my earlier writings.

My first contribution to the problem of the erosion cycle was in 1884; it was then stated that valleys in their early stages "will be narrow and steep walled in regions of relatively rapid elevation, but broadly open in regions that have risen slowly, and I believe that rate of elevation is thus of greater importance than climatic conditions in giving the canyon form to a valley."[1] The last clause of that statement was introduced to correct what seemed to be a then prevailing misapprehension, namely, the explanation of the narrowness of the Colorado canyon by the aridity of its region, instead of chiefly by the recent elevation of the plateau in which it is incised. In an essay on the "Rivers and Valleys of Pennsylvania,"[2] the successive deformations of the Appalachian belt in that state are described as follows: "The great Permian deformation . . . . may have begun at an earlier date, and may have continued into Triassic time, its culmination seems to have been within Permian limits" (p. 193). "During and for a long time after this period of mountain growth, the destructive processes of erosion wasted the land and lowered its surface" (p. 194). The post-Triassic tilting "culminated in Jurassic" time (p. 196); the Tertiary and Quaternary uplifts are merely dated in a general way without specification of rate. In the following pages on the "general conception of the history of a river," it is said: "For the sake of simplicity, let us suppose the land mass, on which an original river

[1] "Geographic Classification, Illustrated by a Study of Plains, Plateaus and Their Derivatives," *Proc. Amer. Assoc. Adv. Sci.*, Vol. XXXIII (1884), pp. 428–32; see p. 429.

[2] *Nat. Geogr. Mag.*, Vol. I (1889), pp. 183–253.

has begun its work, stands perfectly still after its first elevation or deformation" (p. 203), thus perhaps implying rapid elevation; but only for "the sake of simplicity."

In an article on "The Development of Certain English Rivers"[1] the opening of a cycle of erosion was suggested by the words: "Let gradual and intermittent elevation replace depression"; then the establishment of consequent rivers on the slowly emerging sea bottom follows. In a general discussion of "The Geographical Cycle"[2] upheaval without erosion is given first consideration; but after allowing a page to a mere outline of the erosional changes that ensue, it is explained that the outline must be gone over again to fill in details. The first of these is the correction of the too simple assumption of rapid uplift: "It should not be implied . . . . that the forces of uplift or deformation act so rapidly that no destructive changes occur during their operation. . . . . Even during uplift, the streams that gather in the troughs as soon as they are defined do some work, and hence young valleys are already incised when uplift ceases" (p. 487). Then after giving several pages to a fuller account of the erosional changes during an uninterrupted cycle, certain complications are briefly considered, and one of these is that all kinds of upheavals must be considered; "such movements must be imagined as small or great, simple or complex, rare or frequent, gradual or rapid" (p. 499). The manifest reason for not then going on to give detailed discussion of these various kinds of movements is that a good number of pages had already been occupied in explaining a simple uninterrupted cycle introduced by a relatively rapid elevation, and it may be added that such explanation was needed because even that simple scheme was then essentially novel to the readers to whom it was addressed. The complications of the scheme were, therefore, merely mentioned instead of being elaborated.

Complications of the erosion cycle.—"The Complications of the Geographical Cycle" were, however, made the subject of another article a few years later,[3] in which it was said:

[1] *Geogr. Jour.*, Vol. V (1895), pp. 127–46.

[2] *Ibid.*, Vol. XIV (1899), pp. 481–504.

[3] *Proc. Internat. Geogr. Congr.* (Washington, 1904), pp. 150–63.

The elementary presentation of the ideal cycle usually postulates a rapid uplift of a land mass, followed by a prolonged still stand. . . . . The uplift may be of any kind and rate, but the simplest is one of uniform amount and rapid completion. . . . . In my own treatment of the problem, the postulate of rapid uplift is largely a matter of convenience, in order to gain ready entrance to the consideration of sequential processes. . . . . Instead of rapid uplift, gradual uplift may be postulated with equal fairness to the scheme, but with less satisfaction to the student who is then first learning it; for gradual uplift requires the consideration of erosion during uplift. It is, therefore, preferable to speak of rapid uplift in the first presentation of the problem, and afterward to modify this elementary and temporary view by a nearer approach to the probable truth; and this has been for some years past my habitual method in teaching [p. 153].

A brief analysis of a case of slow uplift is then presented:

A special case necessitating explanation by slow uplift may easily be imagined. If an even upland of resistant rocks be interrupted by broadly open valleys, whose gently sloping, evenly graded sides descend to the stream banks, leaving no room for flood plains, it would suggest slow uplift; the absence of the flood plains would show that the streams have not yet ceased deepening their valleys, and the graded valley sides would show that the downward corrosion by the streams had not been so rapid that the relatively slow process of slope grading could not keep pace with it. In such a case there would have been no early stage of dissection in which the streams were inclosed in narrow valleys with steep and rocky walls; the stage of youth would have been elided and that of maturity would have prevailed from the beginning, but with constantly increasing relief as long as uplift continued [p. 154].

The closing statement as to "constantly increasing relief as long as uplift continued" evidently deserves correction and receives it in the second phase of sharp-crested ridges in Penck's first ideal cycle. A following statement: "Examples of this kind must be rare," perhaps needs correction also; but except in the case of weak rocks that remains to be proved. My writings are to my regret deficient in not giving any special attention to the modifications that the scheme of the erosion cycle should receive in the case of weak structures, such as coastal plains with unconsolidated strata.

Definition of the initial surface.—The fact that none of the above brief allusions to cycles of slow initial uplift are accompanied by detailed discussions of the peculiar features that should distinguish such cycles from others of rapid uplift, perhaps gives some color, as far as the publications thus far cited are concerned, to Penck's

criticism that my scheme of the cycle excludes erosion until after upheaval has ceased. There are, however, other and later publications yet to be cited, in which the interaction of upheaval and erosion is fully discussed; but with these publications Penck seems to have been unacquainted, for after making the above criticism he goes on to say that an erosion cycle ought to be conceived as including the sequence of forms from an initial lowland to an ultimate plain of degradation (and hence involving the interaction of erosion and upheaval while upheaval continues, and of erosion alone after upheaval ceases), and that such a cycle ought not to begin, like Davis' cycle, with an initial form of completed deformation, but at the moment when deformation first displaces a preexistent lowland (p. 264). This conception of the cycle is good but it is not new. It has already been realized, as may be seen in various illustrations concerning plateaus, mountains, and valleys in my "Practical Exercises in Physical Geography" (Boston, 1908), and in the chapter on mountains in my *Erklärende Beschreibung der Landformen* (Leipzig, 1912). But before entering upon that aspect of the question, a paragraph may be given to Penck's comment, above, on the definition of the initial surface of a cycle of erosion.

A number of my diagrams and various passages in my writings may, if taken literally and alone, have given the impression that the initial surface of an erosion cycle is a surface in its new attitude after upheaval and deformation are completed; this impression may be gained especially from passages where a rapid upheaval is tacitly postulated; in fact in the first account of the cycle in my "Erklärende Beschreibung" the initial surface (Uroberfläche) is directly defined as the upheaved surface (p. 30). But inasmuch as other passages and diagrams make it clear that some of the erosional work of an erosion cycle takes place during any upheaval and that much takes place during slow upheavals, a reader who apprehends the spirit of the whole rather than the letter of a part of the cycle problem must soon understand that the true initiation of the cycle is at the beginning of upheaval, and hence that the initial surface should be understood to be, as Penck says, the surface then upheaved. If my writings have given rise to a misunderstanding on this point, it should be noted that a similar misunder-

standing of the initial surface as the fully upheaved surface would be gained if certain passages and diagrams in Penck's chapter on "Die Erdoberfläche," above cited, were taken without their context. His diagrams of warped, faulted and doomed structures (Sc. Figs. 72, 73, 81) are drawn with non-eroded surfaces. His text includes a statement concerning an initial surface that is very similar to the one above quoted from my "Erklärende Beschreibung," namely: "If we review the development of valleys, we recognize clearly that their first course is defined by the presence of an original slope, down which the water flows. This slope is the initial form" (Sc. 143). In other passages one reads that lateral compression produces crustal folds having arches and troughs, like those assumed by a cloth when it is pushed from one side (Sc. 134); that a table-like highland is sometimes upheaved between two faults (Sc. 135); that the Black Forest and the Vosges, with the trough of the Rhine between them, are striking examples of the sides of a collapsed arch (Sc. 136); that young fault blocks form plateaus with steep slopes (Sc. 147); that an upheaved peneplain takes the form of a highland (Sc. 176); that a zone of compression runs through its cycle of erosion as soon as the compression ceases (Sc. 176): none of these passages mention erosion as accompanying upheaval. But it would be manifestly unfair to cite such passages without their antidotes; for example, that arched areas of the earth's surface suffer degradation during their arching (Sc. 136); and that as soon as a surface is uplifted erosion begins to destroy it (Sc. 146); and other similar statements. The fact is that so many elements enter into the problem of the erosion cycle that it is difficult to state them intelligibly all at once. It might be well to use two terms: the initial surface would then be defined as the surface at the time when a crustal movement began to introduce a new cycle; and the (potential) deformed surface would be defined as the initial surface in its new altitude after movement had ceased, but without taking account of contemporaneous erosion.

Practical exercises on plateaus and mountains.—The treatment of erosion during upheaval as illustrated in my "Practical Exercises" may now be taken up. The exercises are based on an atlas

of drawings, which are all furnished with scales so that definite measures may be made of altitude of upheaval, depth and breadth of valley erosion, and so on; and the accompanying text sets many questions which lead to explanatory and quantitative answers. The first drawing of a plateau shows it at an altitude of 2,550 feet, with a narrow canyon already eroded across it, 750 feet deep at the background and 1,700 feet deep in the foreground, where it is about 1,900 feet wide at the plateau level. The second drawing shows the plateau 4,200 feet high, and the canyon 2,700 and 3,200 feet deep at background and foreground, and over 5,000 feet wide at the foreground top. In the third drawing the plateau is 4,700 feet high, and the background and foreground depths of the canyon are 3,500 and 4,000 feet, its width at the foreground top being 8,500 feet. The fourth drawing shows the plateau height unchanged, the canyon depths 4,000 and 4,100 feet, with its width at foreground top roughly 15,000 feet, and a flood plain about 1,000 wide in its floor. The corresponding questions bring out clearly the idea of progressive erosion during the uplift, as indicated by the increasing altitude of the plateau and increasing dimensions of the canyon in the first three drawings; and of continued erosion after upheaval has ceased, as indicated by the greater dimensions of the canyon in the fourth drawing than in the third, although the plateau has the same altitude in both. Later stages of erosion on the still-standing mass are pursued in smaller diagrams to eventual peneplanation.

The exercise on mountains opens with a drawing of a faintly undulating lowland. The second drawing shows the greater part of the lowland warped up into an arch which curves around from east-west in the right foreground to south-north in the left background, and has altitudes of from 4,000 feet to 7,000 feet along its crest; the arch is cut across where its height is between 5,000 and 6,000 feet—that is, aside from its lowest summit—by the canyon of an antecedent river; other parts of the arch are well incised by the revived streams of the lowland or by new streams consequent on the slope of the arch; but these valleys occupy less space than the undissected flats and slopes of the upland. The third drawing shows only the east-west part of the arch with its crest now raised

to 7,000 feet, or 3,000 feet higher than before, and with the valleys more deeply incised and more widely opened at the top of their slopes, so that they have reduced most of the inter-valley upland surfaces to sharpened ridges. The fourth drawing, limited to the western or south-north part of the arch, shows the greatly uplifted mass to be completely carved into mountain forms, some of which exceed 10,000 feet in altitude; all the summits that rise along the axis of the vanished arch, as well as all the ridges that radiate from the summits, now have sharp crests, but none of the valleys, not even that of the large antecedent river, have any flood plains. The fifth drawing shows the south-north mountains subdued to rounded forms, the smaller valleys opened to gentler slopes, and the valley of the antecedent river with a flood plain. The sixth represents the east-west part of the curved range reduced to hills of various altitudes, between which even the small-stream valleys have flood plains; and for a seventh stage, reference is made back to the first drawing. The cycle is thus carried from an initial lowland through high mountains to an ultimate lowland, three of the drawings representing the interaction of upheaval and erosion, and three more—or four if the first is counted over as the seventh—representing the continuance of erosion after upheaval has ceased.

Inasmuch as these exercises were planned for use in secondary schools, the lowland which is upheaved to be carved into mountains and then worn down to a lowland again is assumed, for the sake of simplicity, to be composed of massive rocks, and as a result the highly characteristic but somewhat complicated process of the development of subsequent streams at the cost of pre-existent streams, and to the profit of the adjustment of drainage and relief to weak and hard structures, is excluded. The same simplifying assumption is made by Penck in the first ideal cycle of his "Gipfelflur" essay; for although the actual Alps have a good number of subsequent ridges and valleys, and a much larger number of subsequent valley-side ravines which exercise a considerable measure of control upon the altitude of ridge crests by serrating them with subsequent notches, and thus reducing the relief of the intervening subsequent knobs, no mention is made of variations of structure or of the development of subsequent valleys in Penck's analysis of

the ideal cycle. These omissions may be justified on two grounds: first, the essence of the problem under discussion does not demand their inclusion; and second, the presentation of a discussion before a learned Academy, in which all sciences are represented, does demand, if the speaker wishes to be generally understood, that he should simplify his problem to the utmost; for deeply learned as academicians are in their own subjects they must not be expected to know much about the subjects of their colleagues.

The deficiency regarding belts of strong and weak rocks in my exercise on mountains is, however, made up in large measure by later exercises on rivers and valleys, based on a series of eight drawings, the first of which shows a larger and a smaller river crossing a lowland district of inclined hard and soft strata, the course of the rivers being at right angles to the strike of the strata; the second and third show the district progressively upwarped with accompanying erosion; and the others show successive stages of still-stand degradation with an appropriate growth of subsequent streams and capture of different segments of the smaller river by branches of the larger river; the last drawing represents the greater part of the district again reduced to a lowland.

Various opinions may perhaps be held as to the correctness and intelligibility of these drawings and as to the efficiency or teaching-value of the accompanying questions; but the exercises have nevertheless been found worthy of translation into German.[1] From my own perhaps prejudiced point of view, I am inclined to believe that the three elementary exercises above cited, as well as several others that are not here cited, treat a variety of problems more clearly and intelligibly than they are treated in most advanced textbooks. For example, the development of platforms in the walls of canyons eroded in plateaus, where a high-level thin cliff-making stratum retreats more rapidly than a stronger, underlying cliff-maker, as in Plate 9, Figure 3, and Plate 10, Figure 4; the pattern of cliff-rimmed plateau margins as seen in plan, Plate 7, Figures 5, 8, 9; the relation of an antecedent river to the consequent streams of an up-arched mountain belt, as in Plate 12, Figure 2;

[1] W. M. Davis and K. Oestreich, *Praktische Uebungen in Physicher Geographie*, Leipzig, 1918.

the visible forms associated with eventual, imminent, recent, and long-past river captures, as in various drawings of Exercise VII, and especially in Plate 26, Figures 11 and 12. If these figures are compared the figures illustrating corresponding problems in advanced textbooks—for instance, the three block diagrams illustrating river capture, in Figure 130, Volume III, of Passarge's "Landschaftskunde"—the value of elaborated graphic aids in the teaching of land forms will be apparent. But whatever opinion is held on this aspect of the erosion-cycle problem. there cannot be any question that the exercises above cited embody precisely the scheme that Penck recommends, namely, that cycles of erosion are opened by the uplift of a pre-existent surface, that they are continued for a longer or shorter time by the joint operation of upheaval and erosion, and that they are completed after upheaval ceases by the operation of erosion alone, which eventually produces a lowland of degradation. Moreover, the recommended scheme is presented with much greater detail in these exercises of 1908 than it is in the pages on the Erosionzyklus in Penck's chapter on "Die Eroberfläche" in Scobel's *Handbuch* of the same date. The "Gipfelflur" essay might, therefore, be more appropriately regarded as an extension of the author's own brief treatment of the interaction of upheaval and erosion in that chapter than as a correction of my fuller treatment of the problem.

The explanatory description of land forms.—A similar treatment of the interaction of upheaval and erosion is also presented in my *Erklärende Beschreibung der Landformen* (Leipzig, 1912), which embodies the lectures that I gave in the winter semester of 1908–9 at the University of Berlin from Penck's chair, while he was absent as visiting professor at Columbia University. The first explanation of the scheme in this book is limited to the case of normal erosion; it is presented in ideal form and is based on the elementary assumption of rapid uplift; the idea of slow uplift with accompanying erosion is presented more fully later, although a brief statement at the outset says that upheaval may be imagined to be either slow or rapid (p. 30). The chapter in which this ideal scheme is presented is followed by one in which its deduced consequences are confronted with a variety of facts, as a test of its

correctness and completeness; and the scheme is thereby found to be in need of various amendments and additions, among which the possible action of various other destructive forces than those of normal erosion and the possible interruption of the ideal cycle by any kind of deformation at any stage in its progress are emphasized. Another chapter is then given to an elaboration of the ideal scheme, and here a special paragraph is given to erosion during upheaval, which may be translated as follows:

> It is important to remember that the erosional processes by no means wait until upheaval has ceased before they begin their attack upon a land surface. A very significant erosional work can take place while upheaval is slowly progressing. An upheaval can, in fact, go on so slowly as to permit a large river to preserve a graded course and gently sloping valley sides, especially if the upheaved mass is of weak structure. Such a river will, therefore, have no youth, but will, Minerva-like, begin its life with maturity. On the other hand many examples can be adduced in which a highland surface preserves its initial form between the stream-cut valleys so little altered in the early stage of a cycle that we are well justified in believing that upheaval in general is accomplished more rapidly than degradation [pp. 146, 147].

Various other allusions are made to a slow upheaval and accompanying erosion; for example, under coastal plains, it is noted that the rate of their upheaval should be considered, as the amount of dissection during upheaval is thereby determined (p. 207); but this idea is not elaborated. Again in the chapter on the marine cycle, slow changes of level are explicitly but briefly mentioned (pp. 463, 518). The most detailed consideration of the interaction of upheaval and erosion is presented in the chapter on mountains, where several excerpts from the drawings in the above-cited "Practical Exercises" are introduced. Here both a slow and a rapid arching of an initial lowland of generally homogeneous structure is considered; if rapid, the arched surface will be drained chiefly by new consequent streams; if slow, the larger streams may persist in their antecedent courses (pp. 256, 257). It is explained that when the upheaval is only partly accomplished, V-shaped valleys are incised between portions of the upheaved but otherwise little changed initial surface (p. 258), essentially as in the early stage of Penck's first ideal cycle in his "Gipfelflur" essay; when a greater upheaval is accomplished, the deeper incision of the nearly

graded streams permits the flaring sides of their valleys to consume the greater part of the upheaved surface and thus to produce sharp ridges (p. 267), essentially as in a following stage of Penck's ideal cycle; but some small unconsumed remnants of the initial surface may still survive at this time. A fully matured stage is then described as follows:

> A long-continued upheaval has now brought about a still greater altitude and the deep attack of erosion has produced a strong relief. As long as the upheaval is active, even the large rivers must have a torrential flow; they will cut down deeper and deeper, but will be still unable to develop flood plains. So deep have they already cut and so well are the valley sides opened upwards that all the higher parts of the upheaved initial surface have now been consumed. The characteristic features of a maturely dissected mountain range—still under the postulate of almost homogeneous structure—are: . . . . sharp peaks and ridges with numerous little rock outcrops but with the slopes generally covered with creeping detritus. The most notable of these features is the systematic arrangement of the slopes, so that all detrital and water streams from every peak and ridge descend along well prepared converging lines into their valleys [pp. 274, 275].

A following paragraph makes mention of the similar summit altitudes usually observed in maturely dissected mountains, and refers to Penck's principle of a limiting upper level of denudation as its cause.

Here a question of nomenclature arises. According to Penck's latest scheme, sharp-crested mountains are described in his "Gipfelflur" essay by a paraphrase above quoted; it is added that their youthfulness prevents their being characterized, following Davis, as mature. But this correction, like the others already noted, applies quite as much to Penck's own earlier terminology of the erosion cycle as to mine. Sharp-crested mountains are not youthful according to his definition of that stage of erosion in the Scobel *Handbuch:* young mountains are there said clearly to exhibit remnants of the upheaved surface, which may be large enough to deserve the name of plateau (Sc. 147; also Figs. 83,1; 84,1). Hence now to call sharp-crested mountains youthful is quite as much a departure from his own earlier scheme as from mine. Let such a departure be made freely if it seems an improvement on previous pronouncements; but it does not seem appropriate

to refer to the departure only as a modification of someone else's earlier scheme without avowing that it is also a modification of one's own.

The further discussion of mountain carving in my "Erklärende Beschreibung" postulates a cessation of upheaval about the time that the sharp forms of maturity are reached; then follow in due course, under the action of erosion alone, the rounded or subdued forms of late maturity and the worn-down forms of old age. It is the prolongation of upheaval after sharp-crested forms are reached, as postulated in Penck's first ideal cycle, and the development of a stage of balance between upheaval and degradation with a resulting maintenance for a time of a constant summit altitude and a constant relief that constitute real advances in Penck's treatment of the erosion cycle; but not also, as he implies, the discussion of the interaction of upheaval and erosion during the attainment of sharp-crested forms. The advances are surely valuable and interesting, even though, as pointed out above, some of the deductions which they include seem, in the absence of full explanation, somewhat insecure.

Closing remarks.—The composition of the three parts of this article has been attended with mixed feelings. The analysis of Penck's "Gipfelflur" essay in the first part was a pleasant duty in so far as it was concerned with the constructive side of his duty. The general review and summary of the scheme of the erosion cycle in the second part was also an agreeable task, as it brought to mind memories of work and progress in association with many colleagues through forty years of busy life. The correction of Penck's corrections in the third part was a disagreeable necessity. It would not have been undertaken but for his exceptional rank as a geographer and for the high standing of the Academy in whose proceedings his essay is published. On both those grounds it has been deemed desirable to show that his adverse criticisms are much less pertinent to my treatment of the erosion cycle than a reader of his essay would be led to suppose, and that the real value of his essay, which is unquestionably large, lies in the extension of the deductive treatment of the erosion cycle with especial respect to a mature stage in which upheaval and erosion are balanced.

SOME NEW FEATURES IN THE PHYSIOGRAPHY AND GEOLOGY OF GREENLAND

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Inglefield Gulf

I. THE OROGRAPHY OF GREENLAND

Since 1916 I have been occupied with investigations in northwest Greenland. Though my work is still unfinished, I feel impelled, before starting upon a voyage around the north coast of Greenland, to lay before the public some aspects of the geology of Greenland which have recently come to my notice.

During my travels in extreme northern Greenland, partly along the coast and partly across the inland ice cap, I was struck by the fact that the Archean formations had here developed in a manner quite unknown in the south of Greenland. The gneiss everywhere forms low level plains, which toward the north are gradually covered by sediments, and as the surface of the ice cap everywhere in the north of Greenland is remarkably low, the obvious conjecture seems to be that the gneiss plains extend right across the country to the east coast. Having made this supposition, it was only natural that I should direct my attention to the development of the gneiss surface in other parts of Greenland. It soon appeared that no attempt had previously been made to arrive at any complete survey of the surface elevation of Greenland. Whoever has traveled in Greenland knows that Alpine peaks of 2,000 meters alternate with lower rounded hills, and that in some places the surface is so low and level as to form true plains. To get a comprehensive view of this varied topography, I made a relief map of the whole of Greenland on a small map on a scale of 1:400,000, marking in the altitudes in seven colors from green for lowland and red for the highest peaks. The material at my disposal was partly the altitudes marked on the maps, partly topographical descriptions and pictures, and partly my own observations along the west and north coasts.

These I have explored by sledge and motor boat in their entire extent, covering much of the ground several times.

The relief map showed that the gneiss surface reached an altitude of 2,000 meters in the northern parts of the country and also at about 70° N. lat., both on the west and east coasts. The rest of the country showed a varied topography of highly different types, apparently distributed quite irregularly.

I soon felt, however, that my relief map was characterized by too subjective a view; I had colored large areas about which next to nothing was known. A cartographer working exclusively on low ground will perhaps regard a certain area as an upland, whereas the same region will seem low to another cartographer surrounded by high mountains. On the west and north coasts, where the ground was known to me through personal investigation, I could guard against error fairly well, but on the east coast the coloring was doubtful. In other words, I had to rely exclusively upon the figures given on the maps.

If we generalize some small region in Greenland, e.g., a trade settlement, we get, as a rule, the following picture: Off the coast a number of low skerries, a little farther inland hills—a number of peaks which for each locality have nearly all the same elevation. This is practically the case everywhere in the gneiss area, whether it be low and level, or upland with evenly rounded hills, such as were carved out by the action of the inland ice, or rugged peaks formed by the action of local glaciers and weathering after the ice age. Everywhere the numerous almost equally high eminences seem to be the remains of a once level plain, the true surface of the original Greenland, which has subsequently been more or less dissected by erosion. It now became my object to gain some idea of this original peneplain.

On a large map of Greenland I marked all known heights (about 1,200) in their proper places, and projected each figure at right angles to a line parallel with the coast, marking it as an ordinate on the line. Hence for each figure there is a corresponding point at a greater or less distance from the line, according to the altitude of the peak in question. In a locality with many figures the points nearest the line are derived from the skerries, next come some

points of intermediate height from the littoral regions, and finally the numerous almost equal altitudes showing the higher topography. From the distribution of the points it may be ascertained whether a locality is high or low, but we learn nothing about the various erosion forms, such as the rounded formations due to the action of the inland ice or the alpine formations caused by the local glaciers. In nature the latter always seem higher than the former. By connecting the highest points, a fine zigzag line will appear, showing the average elevation of the peaks. In this I succeeded in constructing the two profiles, Figures 1 and 2, for the west and east coast, respectively. These, however, call for a more detailed explanation:

Fig. 1

The west coast profile (Fig. 1).—It will be seen at once that the district of Frederikshaab seems to be remarkably low, a single peak, however, rising to the height of the surrounding areas. This appearance s not due to the district being low in fact, but is caused by the defects of the map, as practically only the skerries are charted. From a ship at some distance from land it is plainly seen that the whole district is high, of the same elevation as the areas to the north and south of it. Moreover, there are a number of peaks near Holsteinsborg which rise above their surroundings and show plainly in the profile. These peaks, however, consist of iron gneiss, they are found only near the coast, and the regions behind them are much lower. Special petrographic conditions have been united to form an isolated high area, which must not be taken into

account when considering the elevation of the otherwise uniform gneiss tracts. The same applies to the isolated peaks in the northern part of the profile. Along the northwestern coast I have ascertained that these isolated peaks did not everywhere consist of gneiss but of later eruptives such as granite, syenite, and diorite (e.g., Sanderson's Hope and Devil's Thumb). Hence, strictly speaking, they should not have been included, but I prefer to differentiate them only from sediments and basalts, as most of the east coast is too little known to discriminate special granite areas.

Apart from the above-named easily explicable irregularities in the west coast profile, it will be seen that the country, from an elevation of about 2,000 meters in the south, slopes gently toward the north, until, slightly to the south of 70° N. lat., it has become quite low. After that it rises again very suddenly to 2,000 meters, only to drop again toward the north until the gneiss surface at about 79° N. lat. is covered entirely by the sea and sediments.

The east coast profile (Fig. 2) is somewhat more intricate. Thus the country suddenly rises to considerable altitudes at Angmagssalik, to drop as suddenly again to low areas. One of the highest peaks of Greenland is found here (Mt. Forel, 2,760 meters), but it is known that the high area only extends a short distance into the inland ice, so that we have here a distinctly high alpine area, well isolated from the surrounding low regions.

There can hardly be any doubt that here we have a tract which, from its peculiar hardness, has resisted erosion, or, more probably perhaps, a horst moving independently of the rest of Greenland. The numerous earthquakes at Angmagssalik favor this conjecture. Some distance to the north of Angmagssalik the gneiss surface has become so low that it is quite covered by basalt. The gneiss appears again in Scoresby Sound, but it is no longer low, the surface lying at a height of about 2,000 meters. With one single interruption to the north of Franz Joseph Fiord, where the inland ice extends to the sediments, we may now trace it up to 82° N. lat., where it has become so low at Nordost Rundingen and at the head of Danmark Fiord that it disappears below the ocean. The northern part of the profile shows some few isolated peaks rising above their surroundings. We know too little as yet to explain the occurrence

of these peaks, but I take it that, as on the northwestern coast, these are more resistant granite areas, which are presumably of later origin than the surrounding gneiss.

The east coast profile, if we do not take into consideration the isolated alpine area at Angmagssalik, thus shows that the gneiss surface from the southernmost point drops toward the level of the

FIG. 2

sea until 70° N. lat., where it rises abruptly to an elevation of 2,000 meters, and then again drops toward the north until at 82° N. lat. it disappears beneath the sea.

The astonishing similarity between the two profiles strikes one at once. Both slope from 60° N. lat. toward 70° N. lat., with a drop of about 2,000 meters; then the country rises abruptly again to 2,000 meters, only to drop again to sea-level at about 80° N. lat.

These facts quite naturally led me to a closer study of the altitudinal conditions of the inland ice cap, in order to ascertain, if possible, an actual connection between the two coastal profiles.

The material from which we can form some idea of the altitudinal conditions of the inland ice is extremely slight. In recent years, however, some journeys have been made across the country, which gain significance in this connection. Farthest south we have Nansen's journey in about 65° N. lat., with 2,700 meters as its greatest height. This is succeeded by De Guervain's journey (about 68° N. lat., 2,500 meters), J. P. Koch's journey (about 75° N. lat., 3,000 meters), Knud Rasmussen's (1) Thule expedition (about 79° N. lat., 2,200 meters), and (2) Thule expedition (about 81° N. lat., 1,200 meters). Peary's journeys in 1892 and 1895 cannot be used for our purpose, as he only states few altitudes in quite general terms. (On his map no heights are given.) One more journey, however, comes into consideration, viz., Nordenskiold's famous expedition in 1870. After Nansen's journey Mohn calculated Nordenskiold's material, and thought he was able to ascertain therefrom that if Nordenskiold had gone straight across the inland ice his greatest height would have been only 2,360 meters. This point would be situated some distance north of De Guervain's route. Hence, looking at the figures at hand, we have from south to north 2,700, 2,500 (2,360) meters south of 70° N. lat., and 3,000, 2,200, 1,200 meters north of 70° N. lat. The figures have been marked in Figure 3, where the two (here somewhat diagrammatic) coastal profiles are seen and the inland ice profile in the middle of Greenland is divided into two halves by a line passing through the highest points of elevation on the inland ice reached on the individual journeys.

As will be seen, there is a distinct depression right across Greenland, a depression which shows itself not only in the altitudinal conditions of the inland ice but also appears plainly in the topography of both the east and west coasts.

II. ALTITUDINAL CONDITIONS OF THE INLAND ICE CAP

The profile of the inland ice cap (Fig. 3) shows that in Greenland there are two centers of glaciation, a large one in the north, and a

smaller one in the south. The line of demarcation between them is formed by the above-noted depression. The recent expeditions

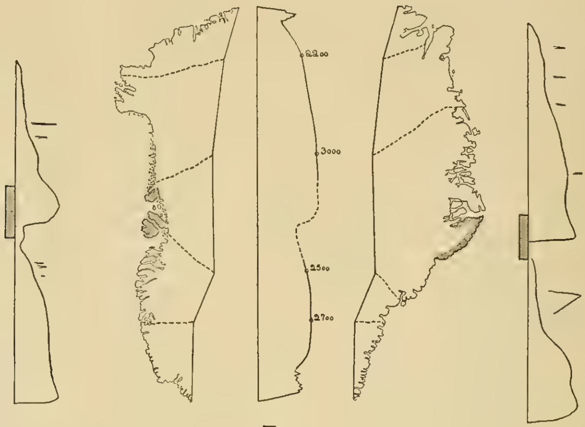

FIG. 3

enable us to mark, roughly, contour lines on the inland ice. This has been attempted in Figure 4, where the proportional heights of the two glacial centers appear very plainly.

FIG. 4

The northern center of glaciation is known from the following expeditions: Peary, 1892 and 1895; Einar Mikkelsen, 1910; Knud Rasmussen, 1912; J. P. Koch, 1913; Knud Rasmussen, 1917. Of these expeditions Koch's is the most important, as it crossed the ice cap very near the place of its greatest elevation. This expedition therefore gives a complete profile of the northern center of glaciation. All the other expeditions took place in the border zone.

The southern limit of the center of glaciation is not known from any expedition, but must presumably be situated slightly to the

north of 70° N. lat. The surface probably inclines pretty much toward the south in this place. Along the west coast high border areas are found in the district of Umanag, Pröven and the southern portion of Upernivik. The surface of the ice cap is high everywhere, in most places about 1,000 meters. From Koch's expedition we know that the 2,000-meter curve is surprisingly close to the coast east of Pröven. In Melville Bay the borderland is low and almost entirely concealed by the ice cap whose margin thus drops to sea-level in this place. From the inmost nunataks it is seen that the 1,000-meter contour is far from the coast.

In extreme northern Greenland the altitudinal conditions are well known on account of the numerous expeditions. Here we can mark the 1,000-meter, 1,500-meter, and 2,000-meter contours with great precision (Fig. 5). It will at once be evident that comparatively large areas of the inland ice cap are below 1,000 meters, and that this contour takes a very irregular course determined by the large fiord glaciers. Especially the Humboldt Glacier and the Petermann Glacier may be traced far into the ice cap. In almost the whole of north Greenland the margin itself is at an altitude of about 500 meters. Einar Mikkelsen's expedition, with its low altitudes, in northeast Greenland, affords good proof that the gneiss surface generally is very low here. To the west of Dronning Louises Land the 2,000-meter contour again approaches land, and everywhere, where it has been possible to get a view of the inland ice from Franz Joseph Fiord and Scoresby Sound its surface has been very high, near 2,000 meters. From Koch's expedition we learn that considerable stretches of the inland ice are above 2,500 meters in northeast Greenland, whereas only a small area is 3,000 meters or upward. The latter area is situated about midway

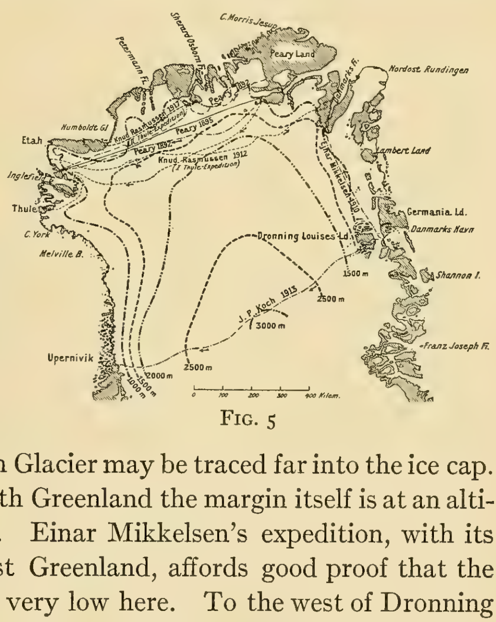

FIG. 5

between the east and west coasts but remarkably far from the north coast.

The marginal zone of the inland ice cap is determined by (1) the substratum, and (2) the climatic conditions. The limit of the marginal zone may, as a rule, be put at the 2,000-meter contour (in extreme northern Greenland perhaps at the 1,500-meter contour) Within this line of demarcation no melting takes place, and only exceptionally do we find traces of inequalities in the foundation.

Our knowledge of the inland ice cap is now so intimate that we may, with fairly close approximation, predict the conditions the traveler will meet with in the marginal zone. From north Greenland especially three types are known:

1. *The littoral region consists of gneiss peaks which speedily change into plateau-like tracts toward the interior.*—The elevation of the ice edge is about 1,500 meters, and the 2,000-meter contour approaches the bordering land. In the months of July and August a narrow melting zone is formed, too narrow to give rise to very considerable streams. After a short journey we reach the 2,000-meter contour and have now entered a level plain of dry and loose snow. Examples are the west coast from 71° to 73° N. lat., and the east coast from 71°to 76° N. lat.

2. *The littoral region consists of fairly low gneiss tracts which extend far into the interior and show a very irregular surface.*—The elevation of the ice edge above sea-level is, as a rule, low. The surface is irregular with nunataks extending far into the ice. There are irregular systems of fissures which prevent the forming of rivers or lakes. The distance to dry firn snow is rather long. Examples of this type are the west coast from Upernavik to Cape York, and the east coast from Germania Land to Nordostrundingen.

3. *The littoral region is formed by gneiss plains or fairly low sedimentary plateaus.*—The elevation of the ice edge above sea-level is about 500 meters. The ice edge is smooth, free from cracks, and easily traversed. Melting occurs in July, and at the close of this month the thin layer of snow had melted about as far as up to the 1,500-meter contour, above which there is dry and loose snow. Near the ice edge there are many small rivers at right angles to it and some few longer rivers and lakes. An example is furnished

by the whole of the north coast from Cape York to Nordostrundingen. Of course there are numerous local deviations from these types.

The southern center of glaciation is known from the following expeditions: Jensen, 1878; Nordenskiold, 1883; Peary, 1886; Nansen, 1888; Garde, 1893; De Quervain, 1909 and 1912. Of these expeditions only two (Nansen, 1888, and De Quervain, 1912) crossed the ice cap; the rest were limited to the border zone on the west coast. Nansen's route cut the center of glaciation near the point of its greatest elevation, and there can hardly be any doubt that this point with its 2,700 meters is about 300 meters lower than the northern center of glaciation. A rather narrow ridge, with an altitude of 2,500 meters and upward, is found from about 62° N. lat. to a point south of 65° N. lat. The 2,000-meter contour everywhere runs near the border of the country. Along the west coast the contour gradually bends inward as it approaches the depression. To the east of Disko Bay great areas of the ice cap are below 2,000 meters. The contour along the corresponding portion of the east coast takes a very irregular course, curving round the high country at Angmagssalik, which forms a small independent center of glaciation. North of this point we are without any knowledge whatever of the inland ice.

The marginal zone shows two types of which the southern one is known from Jensen's, Nansen's, and Garde's expeditions. The borderland consists of high alpine peaks. There are many nunataks, and the edge of the ice cap is high. Locally there are many crevasses and surface moraines. After a comparatively short journey we have passed the 2,000-meter contour and have now entered upon the level dry snow plain. The snow in the marginal zone melts off in June, July, and August. Very considerable streams are not found in the narrow, greatly sloping marginal zone with its numerous fissures.

The second marginal type is found to the east of Disko Bay. The land is well known here from Nordenskiold's, Peary's, and De Quervain's expeditions. The littoral region is low but rather irregular, for which reason the surface of the inland ice is very uneven. The 2,000-meter contour is far inland, which causes a

broad melting zone. Numerous large rivers and many lakes are formed, and locally, crevasses. Beyond the altitudinal conditions the marginal zone shows few similarities to the marginal zone of north Greenland and, on the whole, the conditions are unfavorable to travelers, summer making itself much felt far into the ice cap.

III. THE FORMATION OF ICEBERGS

Now having considered the surface of the inland ice, let us turn to its glaciers and their products, the icebergs.

Sailing northward along the west coast of Greenland, we shall, as a rule, meet the first bergs near Julianshaab. Sometimes they are numerous when derived from the east coast, but they may be scarce or entirely lacking. From Frederikshaab as far as to Egedesminde icebergs are rare. Around Disko, however, they abound in great numbers and from there on they are of common occurrence until Cape York has been passed. Here they suddenly decrease in number, and north of 80° N. lat. they entirely disappear. This circumstance alone shows that the formation of bergs does not take place along the entire edge of the inland ice, and if we look more closely into the case it becomes evident that the greater part of the bergs of west Greenland originate from only a few glaciers but these are exceedingly productive.

Along the entire coast from Julianshaab to Egedesminde the production of bergs is quite insignificant. Almost all the glaciers of the inland ice push down into the head of long narrow fiords and many of the fiords are so shallow at the head that no bergs can be formed. Not until about 69° N. lat. do the bergs occur in any great number, and there we find Greenland's most productive glaciers. The greatest output of bergs no doubt comes from the glacier in the so-called ice fiord at Jacobshavn, but also the Torsukalak and Garajag glaciers are exceedingly productive.[1] From these three glaciers, which are situated within the compass of one and a half degrees of latitude, proceed nearly all the bergs in Disko Bay and Northeast Bay. Only a few are formed along the coast north of the Garajag Glacier. Both Upernivik's and Gieseke's

[1] "The united great glaciers, pouring down to the Karrat Tafiord at 71° 45′ N. lat., are, without doubt, as productive as the Garajag Glacier at the southern corner of Northeast Bay."—Morten P. Porsild.

ice fiords have incorrectly been famed for their numerous bergs. Although a considerable number of bergs occur in summer in the northern part of Sugar Loaf Bay and in Alison Bay east of Amdrup Island, there is no very great output. My investigations in Melville Bay showed that the greater part of the numerous glaciers, which have come down to the sea, only produce few and small bergs. An exception, however, is formed by the King Oscar Glacier in the middle of Melville Bay. It is situated in the very place where the coast bends almost at right angles from south to west, this glacier being thus fed both from the east and the north. Almost all of the numerous bergs, which are nearly always found aground on the many banks and skerries in Melville Bay, come from this glacier.

Few of the numerous glaciers in the Cape York district form bergs, and those that do, only very few. The great Humboldt Glacier, in spite of the great accumulations in its capacious basin, moves very little and forms very few bergs, but here a fresh factor comes into play, viz., the sea ice which hinders the formation of icebergs. That is the reason why, practically speaking, no bergs, or at any rate very few, are produced along the entire north coast from the Humboldt Glacier in the west to Germaine Land on the east coast. Taking this factor as our point of departure, it will be possible to divide all the glaciers of west Greenland into a series of types:

1. *No bergs or very few bergs are formed.*—The glacier rests on land, or if it reaches the sea it moves so little that bergs are only formed at long intervals. Sea ice, if found before the front of the glacier, is not influenced by it, or only very slightly. Nearly all the south Greenland and the majority of the north Greenland glaciers from 71° to 81° N. lat. are examples.

2. *Bergs may break away daily all the year round.*—The glacier comes down to the sea on an open coast where no sea ice is formed in winter so that there is no hindrance to the formation of bergs. Of this type are the glaciers at Cape Alexander, in 78° N. lat.

3. *At intervals of some months bergs are suddenly formed.*—The glacier reaches the sea in a fiord whose mouth is blocked, partly by a submarine moraine and partly by icebergs which have run aground

on it. The water streaming out from under the glacier is dammed up until, the equilibrium being disturbed (most frequently at spring tides), water and bergs are pushed out of the fiord with catastrophic force. Sea ice never prevents the catastrophe. The sole example is the ice fiord at Jacobshavn.[1]

4. *Bergs are formed once a year.*—The front of the glacier is blocked up by sea ice part of the year, so a wall of compressed icebergs is formed in front of, and on, the glacier. In the course of the summer the ice melts off, the bergs often break away with great violence, are shattered, and float away. Porsild has taken the description of the Tormkatak Glacier as the type, but nearly all productive glaciers in west Greenland belong to this type.

5. *Bergs are formed at intervals of a few years.*—In deep bays and fiords of Melville Bay sea ice floats out only in particularly warm or windy summers. The front of the glacier is thus for a brief succession of years blocked up by sea ice so that the bergs accumulate on top of each other, forming an ice conglomerate which freezes into one block after each summer. By degrees a barrier of crowded bergs forms in front of the glacier, and when this barrier of ice conglomerate finally floats off, it may be carried far and wide before it is suddenly scattered into small fragments. In years when there is no ice, more particularly, this kind of berg is very common in the north of Melville Bay.

6. *Bergs are formed at intervals of many years.*—The sea ice remains so long before the front of the glacier that the bergs are fused into a huge ice field with a level surface and without any sharp boundary line toward the glacier at the rear. Toward the perennial sea ice, however, there is still a boundary line. In this way many kilometers of the glacier tongue may float upon the water. The Ryders Glacier in Sherard Osborne Fiord is an example.

7. *Permanent sea ice prevents the formation of bergs.*—On account of the climatic conditions at the inner end of deep fiords, the sea ice as well as the projecting tongue of the glacier increase in height, the annual precipitation finding no outlet. For this reason no

[1] This and the following type have been described by M. P. Porsild in "Om de gronlandske Isfjordes saakaldte Udskydning," *Geografiska Annaler,* Ang. I, Häft 1, Stockholm, 1919.

line of demarcation can be drawn between the sea ice and the glacier. The sea ice in the fiord moves with the glacier almost as far as to the mouth of the fiord, forms fissures, and pushes moraines over projecting headlands or islands in the fiord. If such a fiord is for some reason or other emptied of its ice, numerous floes are formed which may rise from one to several meters above the water. Such floes which, if they are very thick, may thus form actual bergs, are known from Nare's expedition as "Paleocrystic Ice." In the mouth of Robeson Channel they are very common. They are formed in many of the fiords along the north coast of Greenland and Grant Land. The largest Greenland glacier of this kind is the Ostenfeld Glacier in Victoria Fiord.

The glaciers of the east coast have been much less studied than those of the west coast. From Germania Land to, and including, Scoresby Sound, all the glaciers of the inland ice terminate in the heads of deep fiords, and few of them produce bergs in any number worth mentioning. The southern part of the east coast, on the other hand, has several fairly productive glaciers. According to the Eskimos, the largest and most productive glacier is found in Kangerdlugssuag Fiord in 68° N. lat.

It is evident then that icebergs are not formed in extreme northern Greenland. Further it is seen that the bergs along the west coast proceed chiefly from three[1] large glaciers around 70° N. lat. and along the east coast around 68° N. lat.

If we look at Figure 4 we shall see that the productive glaciers both on the east and west coasts are situated exactly at the ends of the great depression across the inland ice. The two centers of glaciation press the ice into the depression which has its outlet chiefly to the west (where there is no basalt under the ice) *through the Jacobshavn, Torsukatak, and Garajag* (Karaiac) *glaciers, and to a somewhat less degree to the east through Kangerdlugssuag.*

IV. THE OROGRAPHIC ELEMENTS OF GREENLAND

The provisional geological survey of Greenland having been ended in 1917, I shall now make an attempt, based on our present knowledge, to divide the country into large orographic elements, an

[1] See footnote 1, page 52.

attempt which will rest more on a geographical than a geological basis (Fig. 6).

By its situation Greenland belongs to America, but it cannot be denied that there are many European features in the geological structure of the country.

Fig. 6

1. *The southern gneiss area.*—This area comprises the whole of south Greenland to the south of 70° N. lat. The country rock, with some few exceptions, consists of gneiss and granite. As will be seen from the profiles, the surface slopes from south to north. The east coast, however, is, on the whole, somewhat higher than the west coast. The regions round Angmagssalik must be regarded as a separate unit. Morphologically all gradations are found from a pronounced alpine topography in the south to quite low plains in the north. Almost everywhere the rocks consist of a uniform light gneiss (Archean), but in the south numerous batholiths (Algonkian?

and Devonian?) are found. Sediments are found only in a small area in the extreme south. It is the so-called Igaliks sandstone, a reddish unfossiliferous sandstone with many diabasic dikes. It has formerly been classed as Devonian but must now be regarded as somewhat earlier (Cambrian-Ordovician). In the west, and especially in the east, the northern part is covered by basalts.

The gneiss area shows no great fissures or cleavages, but this may be due to defective examination. It seems natural to refer it to the great Canadian shield which, as we know, is distinguished by its great uniformity.

2. *The northern gneiss area.*—This forms the greater part of the northern half of Greenland. On the south the limit is formed by the above-noted depression at 70° N. lat. It is limited on the west by Baffin Bay. Toward the north the gneiss can be traced as far as Kane Basin and to Danmark Fiord on the east coast. Toward the Atlantic there are great fracture lines of which the inmost form the eastern boundary. The surface slopes gently from south to north. There is, however, another dip with an east-west trend. Hence the lowest tracts are found in northwest Greenland. The gneiss is very uniform everywhere; batholiths occur but have not yet been examined. In the Cape York district there seem to have been tectonic disturbances (in the Ordovician?), though to no great extent. In the north great portions of the gneiss surface are covered with sediments. In the east, too, in Dronning Louises Land, there are sediments. This gneiss area, too, is naturally connected with the Canadian shield.

3. *The great Paleozoic transgression in northwest Greenland.*[1]—In the south the sediments may be traced to a line running from Cape York to the head of Danmark Fiord, in the east they reach the Atlantic over a short stretch, on the north they are bounded by a folded chain whose southern boundary runs from a point some distance south of Fr. Hyde Fiord to Polaris Harbor in Robeson Channel. Westward the same strata are found over great portions of the Arctic archipelago, and the transgression has already been known from these parts since the middle of the last century. Everywhere the strata lie almost undisturbed on the gneiss surface, the

[1] Studied and described by the present writer in *Stratigraphy of Northwest Greenland.*

oldest being farthest south, while toward the northwest we meet with later and later formations. Immediately on top of the gneiss is deposited a red or gray sandstone with conglomerates and numerous diabase dikes (Cambrian ?). Over this is a light limestone with Gymnosolen, then dark limestone with Maclurea (Ordovician), and above this follow Pentamerus limestone, coral limestone, graptolite shales, and trilobite limestone (Gotlandian), and finally coarse sandstone without fossils. The total thickness of the whole series of strata is more than 2,000 meters.

4. *The north Greenland folded chain.*—The entire north coast of Greenland from Fr. Hyde Fiord to Polaris Harbor consists of folded ranges whose age is determined by the fact that the folding is later than the zone with *Monograptus priodon* and earlier than fossiliferous Devonian which is not, however, very well known yet. The folding is continued westward and seems to disappear gradually in the interior of Grinnell Land. From this place it was first mentioned by Feilden under the name of "Cape Rawson Series." The intensest folding is found in the east in the interior of Peary Land. In continuation of the folding a submarine ridge extends to Spitzbergen. This ridge separates the Atlantic from the Arctic Ocean. In Spitzbergen, as is well known, there are strongly folded strata (Hekla Hook). These strata, according to Swedish geologists, form a continuation of the great Caledonian system which is known from Scandinavia and England. In my treatise,[1] quoted above, I have described more closely the Greenland portion of this folding and shown that it is the western end of the great Caledonian system. This element, then, connecting up toward the east, is a European feature in the structure of Greenland.

5. *The great fracture zone on the northeast coast of Greenland.*—This area which, geologically speaking, belongs to the most varied regions in Greenland, is unfortunately but little known. The trend of the fracture lines has been investigated in its main features in the southern part of this area, but in regard to the northern part we are reduced to mere conjectures. With all reserve I provisionally place the innermost fracture line at the western limit of the Carboniferous in 81° N. lat. Thence the fracture line runs west of Lambert

[1] *Stratigraphy of Northwest Greenland.*

Land down to the eastern side of Dronning Louises Land and thence farther on to Franz Joseph Fiord, in which the innermost fracture line shows very plainly, the gneiss plane appearing in the inmost arms of the fiord. The same applies to Scoresby Sound. The fracture lines seem to be grouped with a slightly concentric course fairly parallel to the coast. Liverpool Land forms a horst of gneiss, but otherwise the fractures descend in steps toward the Atlantic. Fossiliferous strata are known from all geological periods except Cambrian and Permian. The marine fossils, as far as they have been studied, fall into line with corresponding European faunas.

On the eastern side of the Atlantic we know a locality which, in spite of its small extension, is very similar to the east Greenland fracture zone, viz., the Jurassic strata on Andrew near Lofoten. Here, too, the strata are separated by a fracture of very considerable size from the gneiss behind. All in all we can say that the Greenland fracture zone, too, is connected with the Atlantic, and tectonically, as well as stratigraphically and paleontologically, shows points of similarity to European conditions.

6. *Greenland's basalt region.*—It has long been known that both the east Greenland and west Greenland basalt areas were formed in the Tertiary period and they have often been mentioned in connection with the Tertiary basalt strata which form Iceland and the Faroe Isles, and are also represented in Scotland and Ireland. Not only do petrographic and stratigraphic conditions tempt us to regard all these basalt occurrences as belonging together, but in a purely geographical respect, also, they form a unit, since they all, the west Greenland area excepted, lie on a large submarine ridge across the Atlantic.

If we look at a map it will at once be evident that the above-mentioned depression across Greenland is situated exactly in continuation of the great submarine basalt ridge. In Figure 3 I have marked the geographical extension of the basalts in the profiles both on the west and east coasts, and the basalts on both coasts prove to be situated at the exact spot where the low gneiss country is suddenly replaced by 2,000-meter high mountains. It would seem that there is a connection between the depression and

the basalt areas of Greenland. If this be correct, all the basalt occurrences geographically form a unit also.

The basalts have protected some of the sediments against erosion, as for instance the well-known fossiliferous strata of Cretaceous and Tertiary origin in west Greenland and a small area with Tertiary marine fossils on the east coast. The conditions of deposition of the basalts, however, are but little known. On the east coast they appear to have been deposited on the northeastern corner of the southern gneiss plane, no fractures intervening. Exactly similar conditions are found in Disko Bay on the west coast. Here we can trace the southern gneiss plane from the low skerries at Egedesminde northward across some reefs and groups of islands to the skerries at Godhavn and in Disko Fiord, where basalt beds of a thickness of 1,000 meters rest on gneiss. Some of the basalts north of Disko, on the other hand, seem to be divided from the northern gneiss surface by cleavages. The elevation of the basalt plateaus is 1,000 meters at Godhavn. In 70° N. lat. the height is 2,000 meters, and north of this it again decreases. The chief center of eruption of the basalt seems to have been about where Vaigat now is. This element in the structure of Greenland, then, forms the western part of a series of strata which has its greatest extension in the Atlantic.

The American elements, then, are the following: (1) the northern, and (2) the southern gneiss planes, which both form parts of the great Canadian shield, and (3) the Paleozoic sediments, which form the northwestern part of the widely extended series of strata which covers great portions of the Arctic archipelago.

Elements showing relationship on the eastern side, with Europe, are as follows: (1) the Greenland part of the Caledonian folding zone, (2) the fracture zone in east Greenland, and (3) the great basalt area which, besides being extended in the Atlantic, is also found at both ends of the depression across Greenland.

V. THE GREENLAND FIORDS

Few countries contain so many and such large fiords as Greenland and yet many of these fiords are still in part ice filled. Geographically they may be divided into three types:

Of these I shall first consider the large fiords along the north coast of Greenland. Most of them cut right through the Caledonian folds and may be traced far into the country as deep canyons in the sediments and farther on as pronounced depressions far into the inland ice (Fig. 5). The fact that even the folded range has been cut through in numerous places favors the theory that these fiords originated long before the glacial period. Petermann Fiord and Sherard Osborne Fiord are both good types of such sedimentary fiords (Fig. 7).

Fig. 7

Fig. 8

A quite different type of fiords is found in the large ice-free area between Egedesminde and Godhavn. These fiords may suitably be called fracture fiords, having originated by the cleavage of the gneiss along its planes of fracture. The best examples are found in the fiords round Holstensborg. The formation of these fiords has been studied by Karnerup,[1] and it is to be regretted that a work of such genius is only accessible in Danish.

The last type is given in Fig. 8. It is seen that large fiords are chiefly found in three places, viz.: round the south point of Green-

[1] *Meddel. om Gronland*, Bd. II.

land and on both the west and east coasts north of 70° N. lat. Large fiords, in other words, are found exactly where the country is high, and as the country gradually becomes lower the fiords gradually become smaller. It will be seen, however, that even deep fiords suddenly disappear near the edge of the inland ice. The largest fiord complexes of the world, Scoresby Sound, Franz Joseph Fiord, and Northeast Bay, practically speaking, do not influence the surface of the inland ice at all. It must, therefore, be supposed that all these fiords are of very late origin and that the erosion is as yet in only a slightly advanced stage.

VI. THE ORIGIN OF THE DEPRESSION

By means of the altitudes shown on the maps, I have indicated, above, evidences for a depression right across Greenland, and I have then attempted to give a comprehensive view of our present knowledge of the elevation, surface, and iceberg production of the inland ice of Greenland. Further, I have attempted to divide Greenland into large geographical and geological elements, and, finally, I have indicated a division of the Greenland fiords.

All this is grouped about facts which lead to conclusions which anyone with a knowledge of conditions in Greenland may draw for himself. In entering now upon some questions of a more hypothetical kind, it is not without a certain hesitation, as I am by no means blind to the fact that our knowledge of Greenland is as yet too deficient to warrant entering into detail. I shall, however, attempt to point out some of the questions whose solution is reserved for the future, and try to indicate on what lines I believe that some of the questions will be answered—in short, point out some of the main features of some of the numerous geographical and geological questions that are still unsolved in Greenland.

The time of the formation of the depression cannot be stated with certainty. We have an indication in the fact that the basalts seem to be connected with the depression; but to infer from this that it was formed in the Tertiary period would be too hasty a conclusion, since it is conceivable that the depression—this division of Greenland into two parts—may date farther back and may have determined the direction of the great Atlantic basalt fissure. A

continent like Greenland will always be a hindrance to the formation of fissures across the country. It would then be only natural that the fissure would take its course where Greenland, considered as a continent, was weakest.

The theory that the depression is simply a direct continuation of the great Tertiary fissure is, however, the most natural explanation. We know that there have been great movements of the earth's crust in mid-Greenland since the Tertiary period, marine fossiliferous strata having risen several hundred meters since then. If the depression is a Tertiary fissure, the consequence would be that the gneiss planes would be displaced vertically along the fissure about 2,000 meters in relation to each other. It is, however, questionable whether so huge a displacement could take place without the ground on the sides being broken. No such phenomenon is known from Greenland, but that may, of course, be due to defective investigation.

The inclination of the northern gneiss plane toward the north may be explained by the fact that its northern part is heavily weighted with sediments. If a fissure were formed right across the country the gneiss plane which carries the sediments would be reduced to about half and therefore be tilted so that the northern part would be lowered and the southern part raised. In the same way it may be assumed that the northern part of the southern gneiss plane has been submerged beneath the weight of pouring out basalt masses. It has been shown above that both in the west and the east basalt is found deposited on the surface of the southern gneiss plane. Toward the west there are no great quantities left, but escarpments of 1,000 meters show that the basalt once had a greater extension toward the south. Eastward much larger basalt areas now rest on the southern gneiss plane, and how far the basalt here penetrates below the inland ice is still unknown. If we imagine the displacement along the fissure taking place in such a way that the southern edge of the northern gneiss plane was raised just as much as the northern edge of the southern gneiss plane was lowered, the displacement for each gneiss plane at most would amount to 1,000 meters. As it is known for a fact that gneiss planes may, under pressure of ice for instance, subside and again rise more

than 200 meters without being broken, it is not inconceivable that the displacement may have taken place along a single fissure or a very narrow fracture zone without the gneiss planes being broken up into smaller areas.

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THE LAVA FIELD OF THE PARANÁ BASIN, SOUTH AMERICA

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This paper is a summary of the most important results of the writer's recent journeys of 8,500 miles, during seven months, in the eastern River Plate region of South America. The late Dr. J. C. Branner, in May, 1921, expressed the opinion that the "trap" field of southern Brazil and adjacent regions was possibly greater in extent than any other. The writer's subsequent field studies have demonstrated that the area covered by basaltic lavas is at least nearly as great as the combined areas of the Deccan and Columbia River basalt fields, heretofore supposed to be the two largest in the world.

Either basalt or diabase ("dolerite") is found almost everywhere in the hydrographic basin of the Paraná River, and extends beyond into the southern part of the Amazons hydrographic basin (Amazonia) and the eastern part of the Rio Paraguay drainage basin. The drainage basin of the Uruguay River, with extensive areas of basalt, probably was, up to very recent times, directly tributary to the Paraná. Structurally all this region is a single vast downfold (geosyncline), bounded on all sides by outcrops of a pre-Cambrian or early Paleozoic basement complex of plutonic and metamorphic rocks. In this complex the major structural trends, so far as known, are northeast-southwest, parallel to the southern Brazil and Uruguay coast line, and to the major axis of the Paraná downfold. Apparently this eastern region of present hill ranges was one of lofty mountains in late pre-Cambrian or early Paleozoic times. Today the highest mountains and ridges are composed either of folded and faulted metamorphic quartzites or of great bosslike masses of syenitic intrusives.

PREVOLCANIC SEDIMENTARY HISTORY

The sedimentary history is relatively simple, exhibiting a rather surprising uniformity of depositional conditions. Non-fossiliferous basal conglomerates, shore-line sandstones, and alluvial deposits are followed in the same depositional cycle by marine Lower Devonian shales and sandstones, deposits of a sea which covered a vast area in the interior of South America.[1] There followed an epoch of erosion which removed much of the Lower Devonian and possibly older sediments. Then, if not, indeed, earlier (pre-Devonian) it would appear that the approximate eastern and northern limits of the Paraná depositional basin were formed. As yet, no great angular unconformity between Lower Devonian and superjacent beds has been determined.

Nearly all later sedimentation in this basin, so far as yet indicated by outcropping rocks, was of the continental type, although some diminutive brachiopods, presumably marine, have been found in the lower coal measures in southern Paraná, and mollusks, more probably brackish-water or fresh-water forms, in the Estrada Nova beds of both São Paulo and Paraná. It is possible that some contemporaneous marine deposits were laid down in the now covered central or western part of the geosyncline.[2] I. C. White's stratigraphic classification[3] applies to all the sedimentary region east of the basalt. The first deposits of the continental sequence were of alluvial, fluvio-glacial, glacial-morainic, floating ice, and palustrine origin, and are found in the Brazilian states of São Paulo, Paraná, and

[1] Fossiliferous Lower Devonian has been found in the Falkland Islands, the province of Buenos Aires, the eastern Andes of Bolivia, on both sides the lower Amazon geosyncline, in Paraguay, and in the Brazilian states of Paraná, Matto Grosso, and Goyaz. In southern Goyaz, twelve miles north of the town of Rio Bonito, the writer found shales lithologically similar to those of Ponta Grossa in Paraná and carrying Dalmanites.

[2] Siemiradski's (*Geologische Reisebeobachtungen in Sudbrasilien,* Sitz. Ber. Akad. Wiss., Mat.—nat. Cl., Bd. 107, Abt. 1, pp. 23–39, figure and plate, Vienna, 1898) locality and age determinations of some supposed Permian marine fossils from the mountains of the Matto Grosso–Paraguay frontier are doubtful. These fossils were worn as charms by Indians and may have come far distant from where Siemiradski supposed. Also, they are not age-diagnostic; it is possible they are as old as Devonian.

[3] *Report on the Coal Measures and Associated Rocks of South Brazil.* In English and Portuguese. Report to the Ministry of Industry, etc. Rio de Janeiro, 1908.

northern Santa Catharina.[1] Alluvial sandstones and shales, coal beds and palustrine carbonaceous and bituminous shales, laid down on low flattish surfaces, perhaps slowly sinking, followed. These are the Rio Bonito beds of Uruguay,[2] Rio Grande do Sul, Santa Catharina, Paraná, and southern São Paulo. The Rio Bonito in Rio Grande do Sul, Uruguay, and southern Santa Catharina rests, so far as known, directly on the basement complex, often with relatively little basal conglomerate. Following the Rio Bonito is the Palermo, a relatively thin formation of shales. Next is the Iraty, also relatively thin, dark bituminous (sapropelitic) shales with some interbedded limestones and cherts, carrying the fresh-water reptiles, Stereosternum and Mesosaurus (also found in Cape Colony) and numerous ostracods. The Iraty appears to have been a fresh-water lake deposit. It outcrops in a northeast-southwest direction for about 800 miles, extending from northern São Paulo to central Uruguay. The cycle was ended by the deposition of clays with a few thin concretionary limestones, some of which have fish and molluskan fossils—the Estrada Nova beds. All the deposits of this first depositional cycle have been referred to the early Permian or "Permo-Carboniferous," but at least the glacial and coal formations may prove to be late Pennsylvanian. The total thickness averages about 1,650 feet (500 meters).

An erosional unconformity intervenes between the sequence just described and the overlying red beds. This unconformity, first noted by I. C. White, was found by the writer in São Paulo, Paraná, and northern Santa Catharina; hence it probably denotes a time break of considerable importance. The lower of the two red bed formations, the Rio de Rastro—only 300 feet thick at the north but apparently thicker in Rio Grande do Sul—has yielded in Rio Grande do Sul a few reptilian remains[3] which appear to indicate its approximate contemporaneity with the whole of the Triassic part of

[1] Glacial beds may some time be found in Rio Grande do Sul. A likely area is in the country between Suspiro and Bagé, particularly near Ibaré in the southern part of that state. The best section of glacial beds now known in Brazil is along the São Francisco Railway on the northern Santa Catharina border.

[2] The writer is indebted to Karl Walther's publications for numerous data on the geology of Uruguay.

[3] The best-known collecting grounds are just south of Santa Maria and on the Rio Grande–Santa Catharina border northeast of the seaport of Torres.

the Karroo of South Africa. Shales and sandstones, inclined, lenticular, and cross-bedded, and a few conglomerates make up the formation. Overlying is the São Bento heavy and cross-bedded sandstones with a few conglomerate beds. Volcanism began after the deposition of an average of 650 feet of the São Bento sandstone.

We have so far outlined conditions in the eastern part of the Paraná Basin. On the north and west in eastern Paraguay, central and southern Matto Grosso, southern Goyaz, and the western triangle of Minas Geraes the deposits of the first cycle are not yet known with certainty, but the red beds there lithologically resemble the Rio do Rastro and São Bento of the eastern part of the basin.

THE PARANÁ BASALTS AND DIABASES

Extent of basalt area.—The sketch map (Fig. 1) which accompanies this paper represents an attempt to outline the present minimum extent of the basalt flows in the Paraná Basin as determined by former geologic explorers in Brazil, by Karl Walther in Uruguay, and the writer in the western triangle of Minas Geraes, southern Goyaz, central and southwesternmost Matto Grosso, western Paraná, eastern Paraguay, northern Argentina, and northwesternmost Uruguay. The boundaries are fairly well determined by prominent erosional escarpments on all sides except in eastern Paraguay and northern Argentine, where the mesopotamian alluvial deposits of the River Plate lowlands, and the Pampean loess, obscure or entirely conceal the bed rock. There is quite possibly a larger area of basalt in Paraguay and Argentina than is represented on the map. Any other possibly important errors, more particularly on the north and northwest boundaries, can safely be attributed to the imperfections in all existing maps. There is at least one considerable outlying area of basalt in southern Rio Grande do Sul not included in the forthcoming figures and not represented on the map. A considerable dome-shaped area around Lages in southeastern Santa Catharina, now stripped of lava cover, is included in the computations.

The basalt flows, as tentatively mapped, now cover an area of over 300,000 square miles (800,000 square kilometers). Assuming the average thickness of the basalt flows as 1,000 feet, their total

FIG. 1.—Sketch map of Paraná Basin, South America, showing distribution of basalt flows. By Charles Laurence Baker.

Scale 1:10,000. 1″ = 160 mi.

volume is about 50,000 cubic miles. This is of the order of volume of a great mountain range. It is certain that the basalt once covered a much greater area, from which it has been removed by erosion during all the latter Mesozoic and Cenozoic. The entire region of sedimentary rocks in southern Brazil, east of the present limits of the flows, is cut by extraordinary numbers of sills and dikes of diabase. They are less numerous in Rio Grande do Sul, but in the other southern states of Brazil one would scarcely ever be out of sight of one or more intrusives if the country was not densely forested. The sedimentary rocks cut by diabases cover an area of about 75,000 square miles (nearly 200,000 square kilometers). Combining the area of present flows with the area along its eastern margin which probably was once covered, we arrive at the total of more than 375,000 square miles (or about 1,000,000 square kilometers).

Even this may be far short of the total original area. At no place did the writer succeed in reaching the limit of the diabasic intrusives. He found them in the basement complex of southeastern Brazil, also cutting sedimentary rocks as far west as the Gran Chaco in the vicinity of Asuncion, Paraguay, and Walther found them as far south as Montevideo. The writer found them in the southern part of Amazonia. A still greater extension is problematical. Nevertheless, in Piauhy and Maranhão, states of northern Brazil, sediments referred to the Permian and Triassic are cut by diabases, and amygdaloidal sheets are intercalated with the youngest sandstones of the "Permo-Trias" series. Great intrusives of diabase which cut sediments as late as the marine Upper Pennsylvanian and the overlying Red Beds, and antedating sediments referred doubtfully to the mid-Tertiary on both sides of the lower Amazon geosyncline, likewise the great masses of trappean rocks forming a part of the extensive mountainous area on the frontiers of Brazil, Guiana, and Venezuela, may be of the same age as the flows and intrusives of the Paraná Basin. There are heavy flows of basalt interbedded with the red continental sandstones of northwestern Argentina, but these the Argentine geologists, somewhat doubtfully perhaps, consider Cretaceous. There are also diabase dikes in the Falkland Islands.

The minimum thickness of the basalt flows, not including what has been removed at the top by erosion, is more than 2,000 feet (White) in the Serra Geral between Lages and the Tuberão Basin in Santa Catharina, 1,550 feet in northeastern Santa Catharina (according to Woodworth),[1] 1,300 feet at Porto União on the Paraná–Santa Catharina border, 800 feet in the Serra do Esperança between Imbituva and Guarapuava in south-central Paraná, at least 1,150 feet not including the basal portion at Porto Santa Helena on the Rio Paraná on the west boundary of the state of Paraná, 1,150 feet without the basal portion at Marcellino Ramos on the Rio Uruguay on the Santa Catharina–Rio Grande do Sul border, probably 1,000 feet or more north of Santa Maria, Rio Grande do Sul, at least 750 feet without the basal portion at Santa Rita on the Paranahyba River on the Goyaz–Minas Geraes border, at least 600 feet without the basal portion at Jatahy, southern Goyaz, and 400 feet in the Serra do Itaquery in central São Paulo. These figures may indicate that the thickest flows are in Santa Catharina, Paraná, and Rio Grande do Sul, but such a generalization is untrustworthy because of the erosion varying in amount from place to place.

Lithology.—The lower sheets intercalated with relatively thick beds of São Bento sandstone are for the most part not included in the thickness given above. These are either flows interbedded with the sandstones, or are intruded as sills. It is often difficult or impossible to choose between these two alternatives since some of the rocks known to be flows have as dense a texture as those known to be intrusives, and the silicified sandstones of the São Bento, intercalated between these lower sheets, may have been hardened by flows or cemented and partially "metamorphosed" after the volcanism, for instance by the mingling of underground waters. There is usually some intercalated sandstone, in relatively minor proportions, in the upper main mass of the lava, but in Santa Catharina and western Paraná no intercalated sandstone was detected in more than 600 miles of traverse. There is accordingly some likelihood that these upper sandstones are more abundant near the periphery of the original lava field.

[1] *Geologic Exploration in Brazil and Chile*, Bull. Comp. Zoöl., Harvard College.

Many of the flows are vesicular, and some even cavernous. Others are very dense, in which case there is some columnar structure. The amygdaloidal fillings are quartz (both common and amethystine), agate, chalcedony, calcite, zeolites, native copper, copper minerals, and green iron silicate. There has nowhere been found any pyroclastic material, or any indication of true volcanoes, although some of the rocks are so greatly decomposed that the original nature is not known. The great number of dikes in the sedimentary area east of the basalt escarpment shows how widespread were the fissures by which the lavas reached the surface, and since the general thickness is maintained far beyond regions where these fissures are visible, we may assume that fissure eruptions were prevalent throughout the entire Paraná Basin. The fissuring, so far as known, was not accompanied by great faulting.

In composition the basalts and diabases ("dolerites") range from andesite and olivine-free augite-porphyrites to typical limburgites with abundant olivine.

Later sedimentation.—Eruptions began during the time of deposition of the upper part of the São Bento sandstone. At first there appears to have been alternation of lava flows and beds of sandstone; later on came the epoch of greatly predominant volcanism. The lava flows were later deformed into the Paraná geosyncline as we find that structure today. The deformation renewed erosive activity on the bounding crystalline areas to the north, northeast, and east, and a supra-basalt formation of sands and conglomerates, called in São Paulo the Bauru formation, was deposited on the rather slightly eroded lava surfaces. Today a vast surface of the supra-basalt formation constituting a depositional plain is found in western São Paulo, southern Goyaz, and the western triangle of Minas Geraes; remnants of smaller extent exist in southeastern Matto Grosso, and on the great divide between the Jacuhy and Ibicuhy rivers in north-central Rio Grande do Sul. The Bauru formation of western São Paulo contains large dinosaurs of supposed Wealden (late Jurassic or early Cretaceous) age. The surface of the supra-basalt formation slopes very gently toward the Alto (upper) Paraná and Paranahyba rivers in the northeastern part of the

Paraná Basin, but the slope may be entirely or in large part depositional. The supra-basalt formation much resembles in character and mode of origin the later Cenozoic deposits of the Llano Estacado of Texas and New Mexico, and like the latter may be of widely different ages at different localities. The only other supra-basalt deposits, besides stream alluvium, yet known, are sediments, probably eolian, of the Pampean loess in northeastern Argentina, western Uruguay, and southwestern Rio Grande do Sul.

Age of the basalt flows.—Assuming that the age of the upper part of the Rio do Rastro red beds is that of the Beaufort beds of the upper Karroo of South Africa, with which they are correlated by Smith-Woodward, and that the Bauru dinosaurs belong to the Wealden, we have an interval between some stage of the Triassic—presumably later Trias—and the beginning of the Cretaceous, during which there were (1) deposition of the São Bento sandstone, (2) the outflow of the basalt, (3) the deformation of the lavas, and (4) a subsequent period of erosion. This would indicate most probably that the basalt eruptions fell within the Jurassic, possibly in the upper Triassic. There is, perhaps, some reason for uncertainty concerning the exact stage of the Trias occupied by the upper Karroo of South Africa and the upper Rio do Rastro of the Paraná Basin. At a time more or less the same as the deformation of the lavas and formation of the Paraná geosyncline, there were formed basins in the crystalline area of easternmost Brazil which became sites of deposition of Cretaceous and early Tertiary marine sediments.

Perhaps contemporaneous was the formation of the long trough within the basement complex which parallels the Atlantic coast line from Campos in easternmost Rio de Janeiro state, to Curityba in Paraná, followed by the valleys of the Parahyba, the upper Tieté, the Iguapé, and Ribeira and covered by Tertiary lake deposits along the upper courses of the Tieté and Parahyba.

Near the time or contemporaneous with the basalt eruptions there was formed the eastern pre-Andine and eastern Andine depositional basin, in which marine sediments were deposited throughout the Jura and part of the early Cretaceous, and continental sediments during the later Cretaceous and Cenozoic. The epoch of outflow of basalt occurred at or near the time of breaking-up

of the supposed Gondwana land and the formation of the South Atlantic Basin.

Physiography.—Upon the deformation of the lava into the Paraná geosyncline the drainage became consequent to the structure. The geosyncline plunged to the southwest, and the master stream, the Paraná and its headwaters tributary, the Paranahyba, occupied the trough of the geosyncline. These two streams follow the structural trough in the lava for more than 1,000 miles; they appear to have come into existence near the beginning of the Cretaceous period, and to have persisted in their courses. The tributaries either took the shortest distance and line of maximum gradient down the flanks of the geosyncline, or assumed courses in the troughs of cross- or subsidiary synclines. A number of the greatest tributaries of the Paraná River still flow in the troughs of the cross-synclines. The basalt is both so thick and so resistant to erosion that there appears to have been little important subsequent drainage adjustment within the area still covered by lava.

The intercalation of quartzose sandstones with the lava flows and the great preponderance of quartzose and other detritus derived from the basement complex in the supra-basalt formation indicate that the surfaces of the basement complex stood higher than that of the lavas on the north, northeast, and east, in which directions the detritus becomes increasingly coarser. This is in contrast to present topographic conditions in which erosion escarpments of the lava stand at higher altitudes than the less resistant sedimentaries, and a part of the basement complex crystallines.

At the point where the Paraná River crossed the southwestern margin of the lava, falls or rapids were originally formed. The lava surface there constituted a base level for all the drainage of the Paraná Basin above that point. On this local base level of the then slightly denuded lava surface were deposited the supra-basalt sands and gravels. Their original surfaces, still in large part intact, sloped very gently southward in southern Goyez and central-eastern Matto Grosso, southwestward along the Paranahyba drainage basin in southeastern Goyaz and the northern part of the western triangle of Minas Geraes, and west-northwestward in western São Paulo. Along the valley of the Alto (upper) Paraná

from north of Porto Tibiriça to the falls of La Guayra or Sete Quedas, for a distance of 250 miles or more, these sandstones have strongly inclined bedding, very delta-like in nature, dipping in the direction of the flow of the river. Should one make the error of considering these sandstones originally deposited horizontally and later tilted, he would compute their thickness in many thousands of feet.

The Paraná River flows in a canyon with walls of solid basalt all the way from the falls of La Guayra or Sete Quedas, to a point 12 miles below the city of Posadas, territory of Missiones, Argentina, a straight line distance of nearly 250 miles. The breadth of the river just above La Guayra Falls is 12,600 feet and its mean depth at low water is perhaps 3 feet. The breadth of the river at the foot of the falls is 262 feet. The height of the uppermost (lowest) fall is 50 feet, but there are eighteen different groups of falls around both sides and at the head of a narrow trench inclined downstream, and 10,750 feet in length. For 100 miles below the present falls there is a difference of 100 feet below high- and low-water levels in the river. The river falls 373 feet in the distance of 40 to 45 miles between the head of the falls and Porto Mendez.[1] There is a strong gradient in the river all the way from the latter place to within 25 miles of Posadas, at which place a cross-syncline in the basalt brings the supra-basalt formation down to the low-water level. With this exception the entire gorge of the river between La Guayra Falls and a point 12 miles below Posadas is cut through very resistant solid basalt, and at no place is the base of the basalt exposed, although possibly some important undermining action has taken place under the low-water surface. Not only are the falls of La Guayra the mightiest in volume in the world, but they are one of the oldest, if not the very oldest, known.

The lowest or great falls of the Iguassú River, now situated 12 miles above the confluence of that river with the Paraná, have a mean fall of about 230 feet, all through solid basalt. The great Iguassú Falls are said to have a volume greater[2] than those of

[1] The writer is indebted for these data to Mr. Wilson Sidwell, C.E., who has made the only accurate survey of the falls.

[2] Probably overestimated, at least as respects mean flow.

Niagara, but they have receded only about one-seventh as fast as those of La Guayra.

Sandstones intercalated in the basalt are less resistant, the vesicular flows decompose and erode more readily than the denser lavas, and local columnar structure aids erosion. The result has been the formation of step and terrace profiles along the valleys both longitudinally and transversely, and of rapids and waterfalls numbered by the thousands, with intermediate stretches of sluggish and ponded waters throughout the entire drainage area of the Paraná Basin. Rapids, waterfalls, and local base levels are also abundant where dikes and sills are found in the sedimentary rocks.

The present topography within the lava area has, in the principal interstream divides, flat meseti-form plateaus capped by lava or by the supra-basalt formation. These plateaus have great extension in all the Brazilian portion of the Paraná Basin, except in Rio Grande do Sul, where erosion has reached for the most part the stage of maturity. The streams have dissected deep canyons and gorges and have falls and rapids. The topography is, therefore, still in the youthful stage of development but one can venture to assert that it is one of the *oldest* known youthful topographies, considering the absolute length of time it has persisted. On the whole the lava field is a plateau with surfaces gently sloping toward the trough of the geosyncline, partially dissected by youthful canyons and gorges, and bounded for the most part by high recessional erosion escarpments. Those portions of the Paraná Basin lying without the lava area have mature topography, very rugged aside from some local base-leveled areas.

The residual soils—products of decomposition of the basalt—are confined in large part to the flat upland interstream surfaces, except in Rio Grande do Sul. The sides and bottoms of the canyons and gorges are largely bare rock surfaces. The rain may pour down for a week, yet the swollen streams with their average high gradients run fairly clear at the end of the deluge. The main reasons for this appears to be the dense cover of arboreal and smaller vegetation which inhibits to a very great extent sheet wash, and the

low gradients of the instream flats. Between the falls and rapids there are long stretches of slack water where there is deposition of detritus.

The rolling uplands of Rio Grande do Sul are grass-covered. The Rio Jacuhy which drains the southeastern part of the basalt area of that state has the advantages of relatively short course and steep gradients to the Atlantic. The local base level of the middle Uruguay, formed by the basalt falls near Salto, Uruguay, and Concordia, Argentina, lies at a relatively low level. These factors, combined possibly with others, have operated to bring about a more advanced stage of erosion over a large portion of the lava region of Rio Grande do Sul.

The five major tributaries of the Paraná in the states of São Paulo and Paraná—namely, the Rio Grande, the Tieté, the Paranapanema and its largest tributary, the Tibagy, the Ivahy, and the Iguassú—have their sources east of the present lava area (all of them except the Ivahy in the crystalline area of the Serra do Mar, very close to the Atlantic Coast)—flow downstream across the sedimentary area, and cut through the eastern scarp of the basalt. It is probable that these rivers have largely persisted in initial courses determined by the westerly slope of the deformed land surface. The only one of the five which shows marked subsequent adjustment is the Ivahy which for a portion of its course flows at the eastern foot of the lava escarpment, shifting its channel down dip in accordance with Gilbert's Law. It is probable that the original surface had greater gradient near its eastern margin than in the vicinity of the geosynclinal axis. This made possible more rapid erosion in the headwater courses of these streams, and perhaps the lava cap was thinner there than farther west. These streams, as well as some original tributaries of the Paraná in Goyaz, Matto Grosso, and Minas Geraes later beheaded by tributaries of the Amazons and São Francisco, originally drained areas of the basement complex which were the sources of the supra-basalt formation. The basalt lies directly upon the basement complex in the headwaters regions of the Rio Grande and Paranahyba.

The Paraná Basin has been land since the Trias and with the possible exception of the Guianan Highlands and the eastern Brazil

crystalline highlands, is perhaps the oldest land in South America. The vegetation of the Paraná Basin has an archaic cast. Araucarians, tree ferns, and primitive angiosperms are characteristic. Among old types of animals, we find lung fishes and primitive birds. The Paraná Basin may have been one of the centers of development and distribution of the present fauna and flora of South America.

Latest movements.—Any diastrophic events of possibly later date than pre-Cretaceous will be difficult to detect in the Paraná Basin. The Atlantic Coast and the alluvial basin of the River Plate, are more favorable regions for their detection.

There is great general similarity in stratigraphic, volcanic, and structural features between the Karroo Basin of South Africa and the Paraná Basin of South America. The land-laid deposits of the Karroo System of South Africa are very similar in mode of origin and fossil content to those of the Paraná Basin. There is a great geosyncline in South Africa also. Du Toit[1] has recently summarized the data on the Stromberg volcanic series and complementary doleritic intrusives of South Africa. He says the intrusives cover an area of fully 220,000 square miles between the twenty-eighth and thirty-third parallels, and originally extended eastward into the Indian Ocean and probably westward into the Atlantic. If outlying tracts are connected, the area of intrusions aggregate more than 325,000 square miles. The dolerites probably date from Rhaetic or Lias, at latest from Middle Jura. The effusive outflows of the Stromberg volcanics occupy the central part of the Karroo Basin and are confined to an area 350 miles long and 150 miles broad with Basutoland as the center. As du Toit points out, the mid-Mesozoic shows in South America, South Africa, Tasmania, Antarctica, peninsular India and in the eastern United States (Newark series) the greatest known eruptions of trappean rocks.

April 24, 1922

[1] "Karroo Dolerites of South Africa," etc., *Trans Geol. Soc. South Africa*, Vol. XXIII, pp. 1–42.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Washington, Henry S. "The Charnockite Series of Igneous Rocks," *Amer. Jour. Sci.*, XLI (1916), 323–38.

Five specimens of typical representatives of the charnockite series of India from the original localities are here re-examined by Doctor Washington, and five new analyses are given. A comparison with the older analyses shows considerable variation. The rocks were also determined by the Rosiwal method. The percentage of minerals given for the hypersthene-granite (charnockite) places the rock in 226′ of the reviewer's system, a normal hypersthene-granite. The feldspar of the intermediate charnockite or hypersthene-quartz-diorite is not determined separately in percentages. The total feldspar is given as 55.5 per cent, but from the description it is impossible to determine the proportions. From the name given to the rock and from the statement, "a great majority of the feldspar grains had a refractive index of about that of Ab_3An_1," the proportion of alkali feldspar must be small, although the statement is made that "the feldspar is, apparently, largely alkalic, some of it showing the microcline grating, while the greater part shows no twinning lamellae." Further in the summary, the range of the rocks is said to be "through hypersthene-quartz-diorites (and possibly monzonites), etc.," indicating the possibility that the position of the rock is farther toward the orthoclase side than the name quartz-diorite would indicate. Basic charnockite gives a mode corresponding to 3312, or normal norite, assuming the feldspar is 95 per cent or more labradorite. The hornblende-hypersthenite or bahiaite is 426.

Washington, Henry S. "Persistence of Vents at Stromboli and Its Bearing on Volcanic Mechanism," *Bull. Geol. Soc. Amer.*, XXVIII (1917), 249–78, pls. 4, figs. 15.

It is pointed out that the vents of Stromboli have been persistent in location for a very considerable time. They cannot, therefore, have originated by explosive agencies, but can best be explained on the basis of the "gas-fluxing" hypothesis of Daly.

Washington, Henry S. "Italian Leucitic Lavas as a Source of Potash," *Metallurgical and Chem. Engineering*, XVIII (1918), No. 2. Pp. 21.

The Italian volcanoes contain at least 10,000,000,000 tons of K_2O, which at the present rate of consumption could "on paper" supply the United States for 50,000 years *if* a profitable method of extraction could be found.

WASHINGTON, H. S., and KOZU, S. "Augite from Stromboli," *Amer. Jour. Sci.*, XLV (1918), 463–69.

It is not the intention to give mineralogical reviews in this column. This paper is simply listed to point out the desirability of having at least three things determined in a rock: (1) a chemical analysis of the rock itself; (2) chemical analyses of the component minerals; (3) percentages of the actual minerals present in the rock. It is known that such minerals as the pyriboles and biotite vary in composition in different rocks, consequently to determine whether there is any relationship between the kind of rock and the composition of the component minerals, all of the factors mentioned should be determined.

WASHINGTON, HENRY S. "Italite, a New Leucite Rock," *Amer. Jour. Sci.*, L (1920), 33–47. Also a preliminary paper in *Jour. Wash. Acad. Sci.*, X (1920), 270–72.

Normal leucitites contain nearly as much pyroxene as leucite. Here is described a leucocratic leucitite, containing about 90 per cent leucite, and to it is given the name *italite.* According to the reviewer's system it is not quite a true leuco-leucitite (1120) for it falls just over the line in the second class. The leucocratic minerals amount to 94.01 per cent while in the leucocratic class the line is drawn at 95 per cent. The rock is, however, the one nearest this position that has been found. A striking characteristic is the high percentage of potash in the analysis, 17.94, or greater by 50 per cent than any previously recorded.

An ejected block from Monte Somma is also described. This resembles the italite but contains melilite as the last mineral to crystallize. The mode given is leucite 60 per cent, melilite 18 per cent, pyroxene 20 per cent, and magnetite 2 per cent. To this melilite leucitite is given the name *vesbite.* In the reviewer's system it is 2120.

Washington proposes *albanite* to replace leucitite for mesocratic types.

WASHINGTON, HENRY S. "The Rhyolites of Lipari," *Amer. Jour. Sci.*, L (1920), 446–62.

Publishes five new analyses of the Lipari rhyolites, a hyalodacite from Monte Sant' Angelo, Lipari, and an obsidian from the Island of Milos. The following refractive indices, determined by Doctor Merwin, are given: Obsidian, Rocche Rosse 1.488–89, from Forgia Vecchia 1.490, from Monte Arci 1.487–89, from Milos 1.490, pumice from Monte Pelato 1.499.

WASHINGTON, HENRY S. "The Chemistry of the Earth's Crust," *Jour. Franklin Inst.*, CXC (1920), 757–815, figs. 6.

Briefly discusses the interior of the earth, mineral and chemical characters of igneous rocks, the average igneous rock, average composition of the earth's

crust, petrogenic and metallogenic elements, comagmatic regions, chemical composition and rock densities, and the relations between rock densities and elevations of continents.

WASHINGTON, HENRY S. "The Granites of Washington, D.C.," *Jour. Washington Acad. Sci.*, XI (1921), 459–70, fig. 1.

Two types of granite occur as intrusives in the granite-gneiss of the District of Columbia, biotite-granite and muscovite-biotite-granite. Two new analyses of the mode of the former are given. The mineral composition places it in 226, very near 225, orthogranite, of the reviewer's system. It contains 6 per cent epidote besides the essential constituents indicated in the name. Two new analyses are given of the two-mica-granite, but no modal percentages. Both types show cataclastic texture. Epidote is developed in the portions of the biotite-granite most metamorphosed, but is absent in the two-mica-granite. It is said to be apparently wholly secondary.

WASHINGTON, HENRY S. "Obsidian from Copan and Chichen Itza," *Jour. Washington Acad. Sci.*, XI (1921), 481–86, fig. 1.

Describes two Yucatan obsidians, one black, the other brown, from implement cores and beads. Washington thinks both types of obsidian came from the vicinity where found. The black obsidian is of the usual type, the brown one, however, belongs to the alcalic series.

WASHINGTON, HENRY S. "The Lavas of the Hawaiian Volcanoes," *Hawaiian Annual for 1922*. N.p. 1921.

A popular article on the various Hawaiian lavas.

WATANABE, MANJIRŌ. "Cortlandtite and Its Associated Rocks from Nishi-Dōhira, Prov. Hitachi," *Science Reports* (Tōhoku Imperial University), Ser. III, Vol. I (1921), pp. 33–50, figs. 4, photogravure pl. 1.

Intruded in a region of biotite-schist and biotite-gneiss is a small body, possibly a laccolith. The mass is made up of various types of rocks, all parts of the same intrusion. The inner core is cortlandtite. Above this is hornblendite, which is succeeded successively by thin layers of quartz-bearing-gabbro and quartz-diorite. The cortlandtite consists of greenish hornblende poikilitic with pyroxene (hypersthene and augite) and olivine in less amount, and accessory biotite, apitite, ilmenite, zircon(?), and magnetite. The hornblendite (so called) is a coarse granitoid rock, chiefly of dark minerals, hornblende, less augite than the cortlandtite but more biotite, and finally an unnamed plagio-

clase filling the interstices between the dark minerals. The quartz-bearing-hornblende-gabbro consists of green hornblende, dark-brown biotite, and white plagioclase. No percentages are given but the statement is made that "the first one still predominates to a greater amount than the other (sic)," probably meaning the dark exceeds the light. The plagioclase is said to have refractive indices of 1.550 to 1.573 in different crystals, indicating andesine to labradorite. Quartz is accessory, as is also apatite, pyrite, and magnetite. The quartz-diorite has a thickness of not more than one meter and grades into the underlying gabbro. It consists of quartz, andesine, hornblende, and biotite, with accessory apatite, titanite, zircon, magnetite, and pyrite. If, then, this mass represents a single body, which has been differentiated, it indicates the manner of the separation of the various minerals. "In the dentral and lower part olivine and hypersthene are present, and large crystals of hornblende enclose all other constitutents, indicating . . . . that it was the last phase in the course of consolidation of the magma at this part. Towards the upper layers, olivine and hypersthene decrease in amount and finally disappear in the hornblendite. Here augite decreases in quantity and ceases to show the poikilitic relation to hornblende, while plagioclase appears filling up the interstices of the femic (sic) minerals. In a still upper part formed of gabbro, plagioclase becomes a member of the essential ingredients. A prominent feature of this part is, however, the appearance of quartz, though it is small in quantity. Here this mineral is the phase which was last to crystallize out. Further, approaching the upper marginal part, plagioclase and quartz increase in quantity and form the essential components."

No modal percentages are given but there are chemical analyses of the first three rocks.

WEISE, E., and UHLEMANN, A. "Sektion Auerbach-Lengenfeld," *Erläut. geol. Spezialk. Königr. Sachsen.* Leipzig, 1915, 2d ed. Pp. 57, figs. 3.

This quadrangle contains the three large granite masses of Bergen-Lauterbach, Eibenstock, and Kirchberg, between which are slates, phyllites, and quartzites, metamorphosed by the granite. Various analyses are given, the contact action is described, and the associated dikes of aplite, kersantite, and mica-porphyrite are discussed. Two bowlders of melilite-nepheline-basalt were found at the eastern border of the quadrangle, but the source could not be discovered.

WEISS, GUSTAV. "Beiträge zur petrographischen Erforschung des Unteren Buntsandsteins," *Ber. d. Oberh. Ges. f. Natur.—u. Heilkunde. N. F. Naturw. Abtlg.*, VI (1914). Pp. 14, pl. 1, figs. 2.

The quartz-feldspar-sandstone at Gisselberg, near Marburg, consists of 20 to 30 per cent feldspar and 70 per cent quartz. The feldspar is about half

and half orthoclase and plagioclase. The components are held together by their fine grain, by quartz, and by small amounts of ferritic and claylike substances which originated from alteration of the constituents. An important part of this study is the use made of pairs of alternating coarse and fine layers for the determination of the conditions of sedimentation.

WRIGHT, FRED E. "The Petrographic Microscope," *Jour. Optical Soc. Amer.*, I (1917), 15–21, fig. 1.

Gives a brief description of the petrographic microscope and describes its use in the determination of various optical properties.

WRIGHT, FRED E. "The Petrographic Microscope in Analysis," *Jour. Amer. Chem. Soc.*, XXXVIII (1916), 1647–58.

Discusses the applicability of the petrographic microscope to certain classes of problems of a chemical nature. The differences between an ordinary and a petrographic microscope are described, and the various optical properties used for diagnosis are briefly stated.

WRIGHT, FRED E. "Recent Improvements in the Petrographic Microscope," *Jour. Washington Acad. Sci.*, VI (1916), 465–71, fig. 1.

Describes a sliding objective changer, the removal of astigmatism in the analyzer, the prism method for observing interference figures, and a device for use in the accurate measurement of extinction angles.

WRIGHT, FRED E. "Note on the Lithophysae in a Specimen of Obsidian from California," *Jour. Washington Acad. Sci.*, VI (1916), 367–69.

The lithophysae in a specimen of obsidian from Little Lake, about 40 miles south of Owen's Lake, Inyo County, California, are thought to be due to hydrostatic tension resulting from the contraction of the magma during cooling and outward pressure of the gases set free during the crystallization of the spherulites. The minerals of the spherulites are potash-soda feldspar, tridymite, and magnetite, with some fayalite, and occasional jet black mica.

WRIGHT, FRED E. "A Precision Projection Plot," *Jour. Washington Acad. Sci.*, VI (1916), 521–24, fig. 1.

Describes a stand with a frosted glass top, illuminated beneath by an electric lamp, upon which is placed a stereographic projection net 40 cm. in

diameter, printed on thick, transparent celluloid, and with curves at 1° intervals. The celluloid disk rests on the glass disk and by means of centering screws can be centered to the axis of rotation of an outer steel ring which carries the tracing paper on which measurements are plotted. An accuracy of 0.1° is attainable.

WURM, CLEMENTINE. "Die Mineralien in den Einschlüssen des Basaltes vom Finkenberg bei Beuel," *Centralbl. f. Min. etc.*, 1921, 581–90.

Describes all the minerals found in inclusions of basalt from the Finkenberg region, and discusses their origin and genetic relationships.

ZANTINI, WILLY. "Der Noseanphonolith des Schnellkopfs bei Brenk und die anstehenden Noseanphonolithe überhaupt mit besonderer Berücksichtigung ihres geologischen Auftretens und ihrer Einschlüsse," *Neues Jahrb.*, B. B. XXXVIII (1914), 587–642, pls. 2.

Underlying the Laacher Sea there was evidently a foyaitic magma which solidified at depth as a plutonic rock and its accompanying dikes, and now expressed by numerous inclusions in the extrusives, and in an extrusive noseanite phonolite and its tuff. This extrusive is here described in considerable detail, with analyses and descriptions of the component minerals.

REVIEWS

The Tin Resources of the British Empire. By N. M. Penzer. London: William Rider & Son, Limited, 1921.

This book constitutes a useful reference work for geologists, mining engineers, and others who are in search of information on specific tin-producing districts in the British Empire. The book contains voluminous statistical tables recording the trade in tin within the British Empire and production statistics where such are available. For the Cornwall district production tables for individual mines are given.

As the book does not profess to be primarily geologic there are no geologic maps and the geologic descriptions are commonly short; two geologic sections across the Malay Peninsula prepared by J. B. Scrivenor, Government Geologist of Malaya, are, however, included.

Methods of prospecting, mining, and ore treatment are discussed for certain regions, notably Malaya. The book closes with brief chapters on the "Industrial Applications of Tin," "Prices, Sale of Tin," and "World's Output," and with a Bibliography of forty pages in which the titles are listed geographically with the exception of those which are general in their scope. To the geologist this Bibliography will be found to be less exhaustive and less useful than that compiled by F. A. and Eva Hess, published as Vol. LVIII, No. 2, of the Smithsonian Miscellaneous Collections.

E. S. B.

Determinative Mineralogy. By J. Volney Lewis. Third edition. New York: John Wiley & Sons, 1921. $3.00.

In this new edition Professor Lewis has followed the general plan of the second edition, so far as the blowpipe work and the chemical properties of minerals are concerned. On these points, therefore, the new edition needs no comment, although minor changes, such as the omission of some twenty-five of the rarer minerals and the use of a larger-size page, may be mentioned. The addition of determinative tables for some 290 minerals, covering 138 pages, based purely on physical characteristics, is an innovation of great value which will commend itself both to those who use the book in the field, and those who use it in the classroom.

The physical classification of the minerals is based on streak, color, cleavage, and hardness. Under the description of each mineral, besides the ordinary physical characteristics, there is a note on its associations and occurrence. The use of cleavage in the classification seems to be helpful for the determination of those specimens which show good cleavage; but for those lacking cleavage, it is in some cases necessary to search through several sections before the mineral can be determined. For example, if a specimen of magnesite shows good cleavage, it can be identified readily in section 7; but if it happens to be of the white, massive, unglazed porcelain-like variety, it is not found in the section containing minerals with no cleavage, and search must be made through from one to three other sections to find it.

The method of classification adopted saves many pages, and if the principle is clearly understood, should result in little confusion.

D. J. F.

Fossil Plants, Volumes I–IV. By A. C. SEWARD. Cambridge: University Press, 1898–1919.

Seward's great textbook deals only with Thallophyta, Pteridophyta, and Gymnospermae. The printing is excellent, but there should be more illustrations. Each volume has an excellent index and an exhaustive bibliography. Since twenty-one years elapsed between the appearance of the first and the fourth volumes, there is naturally unevenness in the publication. While the last two volumes are up to date, the first two are somewhat antiquated.

This is now the standard textbook of the paleobotanist. The volumes deal not only with external structures, but also with the anatomic and morphologic features. In short, the book attempts to be a survey of our present knowledge of paleobotany. Every student of the subject will have to start from Seward, no matter what topic touching cryptogamic and gymnospermic plants he may approach.

A comparison with Schenk's *Handbuch* naturally forces itself upon the reader. There is no doubt that Seward's work is a great advance on Schenk's, although the latter is still an authority on fossil angiosperms.

If we compare the usefulness of Seward's book with, for instance, Zittel-Eastman's volume on Invertebrates, we cannot escape the conviction that Seward's book is not intended for determinations. There is still need for a handbook of paleobotany which can be used by the collector for determining fossil-plant genera and, if possible, species.

A. C. N.

Devonian Floras. By E. A. NEWELL ARBER. Cambridge: University Press, 1921.

The author lays down an essential distinction between the early and the later Devonian floras, and discusses the geological age and distribution of the two. The older is called the Psilophyton Flora, and the later, the Archaeopteris Flora, in accordance with the predominant plant types. Among the fossils of the Lower Devonian flora are the newly discovered types from Rhynie in Scotland which are at present the earliest known land plants.

Arber examines in detail the geologic age of different Devonian plant beds, taking into consideration only well-known floras of which the horizons have been more or less satisfactorily determined. He is inclined to accept a highly polyphyletic hypothesis with regard to the origin of the main groups of vascular cryptogams which he thinks to be derived severally from distinct algal types. He realizes that we are at a new point of departure in our knowledge of the evolution of higher plants, and his book is written from this point of view.

A. C. N.

A Catalogue of the Mesozoic and Cenozoic Plants of North America. By F. H. KNOWLTON. United States Geological Survey, Bulletin 696, Washington, 1919.

The book is a new edition of *A Catalogue of the Cretaceous and Tertiary Plants of North America*, much enlarged and supplemented. It includes the whole of the Mesozoic as well as the Cenozoic of North America, exclusive of Greenland and Mexico. The larger portion of the book is an alphabetical catalogue of plants to which is added a biologic classification of genera, an index of genera and families, and floral lists of plant-bearing formations. In his Introduction, Knowlton includes a table which gives the approximate stratigraphic position of plant-bearing beds, to which are added a few well-known non-plant-bearing marine units so that their relative positions may be seen.

The catalogue is one of the most useful books published on the North American fossil floras. A similar catalogue of the Paleozoic plants of North America is much to be desired. There is only one man who can write it—Dr. David White. Will he give it to us?

A. C. N.

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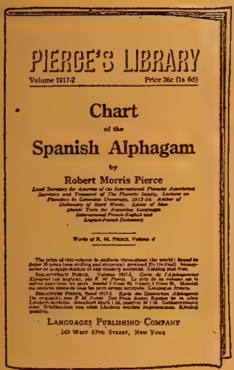

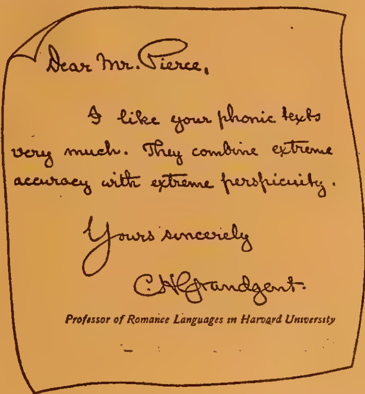

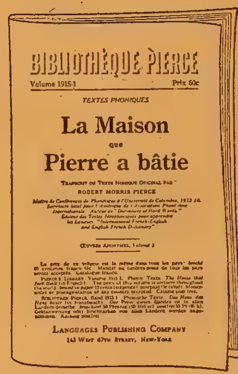

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The Pleistocene of Northwestern Illinois: a Graphic Presentation of the Chief Lines of Evidence. By MORRIS M. LEIGHTON.

Tilted Galena Dolomite over Fossiliferous Loess at the Border of Belvidere Lobe in Winnebago County, Illinois. By MORRIS M. LEIGHTON.

The Physical Chemistry of the Crystallization and Magmatic Differentiation of Igneous Rocks. VII and VIII. By J. H. L. VOGT.

A Venerable Climatic Fallacy. By T. C. CHAMBERLIN.

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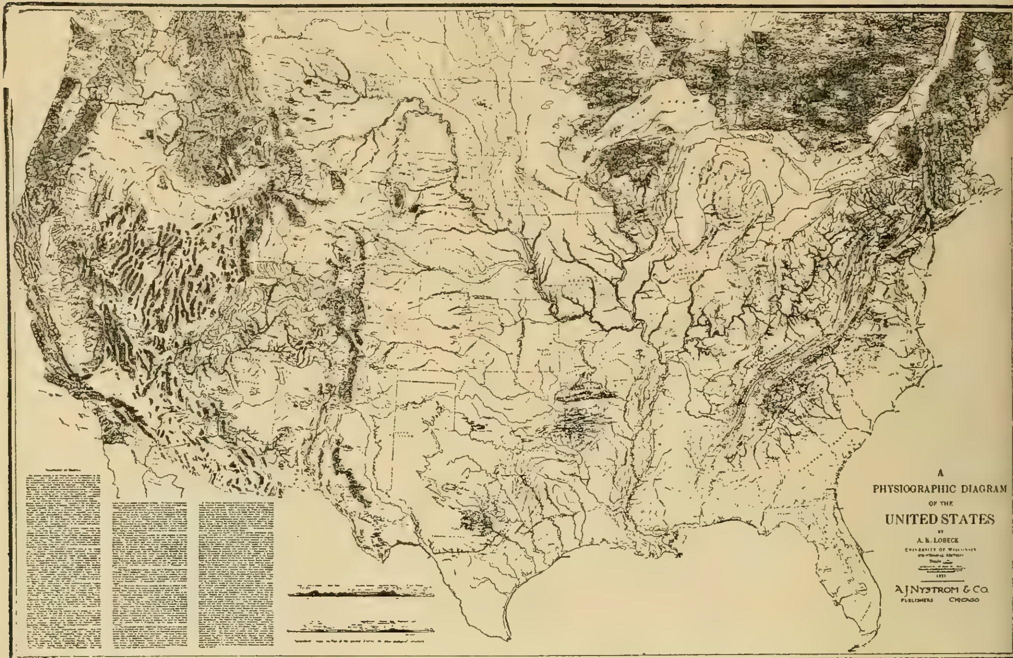
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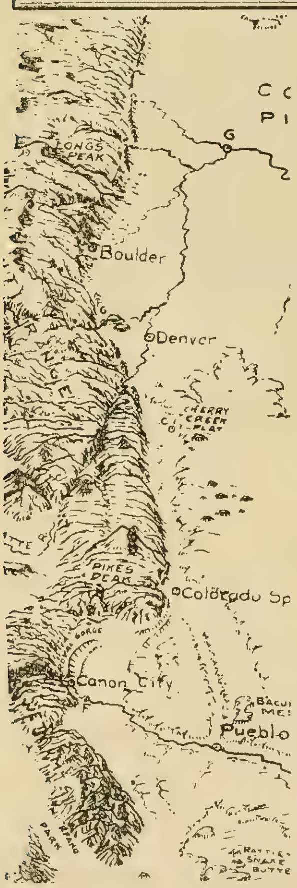
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THE PROBLEM OF THE ANORTHOSITES AND OTHER MONOMINERAL IGNEOUS ROCKS

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The story of monomineral igneous rocks, which occupy today such a prominent place in the problems of petrogenesis, may be outlined in a few words as follows. Formerly no special attention was paid to these rocks. When "simple" rocks were considered sediments, the monomineral silicate rocks were thought to belong to the sedimentary or the metamorphic series. That was, for instance, the case of the Canadian and other North American anorthosites, and Adams[1] was obliged to argue, in 1893, for their igneous origin. Several years afterward the present writer considered the monomineral igneous rocks as derived from those extremely pure magmas, unable to split farther, toward which the differentiation of a complex magma tends. From my own and Brögger's point of view on magmas as solutions of minerals, where the differentiation consists not in the wandering of separate oxids, as was then maintained by Iddings, but in the transfer of those groups of oxids and silica which correspond to the minerals of the future rock, I was led to admit that every igneous rock had its feld-

[1] F. Adams, "Über das Norian oder Ober-Laurentian von Canada," *Neues Jahrb. f. Miner.*, Beil.-Bd. VIII (1893), p. 419.

spathic facies.[1] Vogt referred the formation of the monomineral rocks to the eutectic scheme, and contrasted the "anchimonomineral" rocks with the "anchieutectic." Daly applied his view on gravitative differentiation and his eclectic theory of the origin of the igneous rocks (which is essentially, as he himself states in his admirable and highly suggestive book, *Igneous Rocks and Their Origin*, a further development of my syntectical-liquational theory) to monomineral rocks. In the conceptions of Vogt, Daly, and the writer the formation of monomineral rocks is intimately connected with magmatic differentiation in the liquid state. Bowen, on the contrary, on the basis of his important and suggestive laboratory experiments, attributed the formation of the monomineral rocks to differentiation by crystallization. He considers these rocks as resulting from a gravitative accumulation of crystals in the early stages of the crystallization of a basaltic magma. The essential difference between Vogt, Daly, and myself on the one side, and Bowen on the other, is that according to us the monomineral rocks existed as such in the liquid state, while Bowen does not admit the existence of a monomineral rock in the liquid state. He considers such rocks only as gravitational accumulations of solid crystals during the crystallization of a basaltic magma.[2] For the anorthosites of southwest Baikal, Switalsky presented a third view. He thought that all of these rocks ". . . . originated from a liquid mass," but they were formed from sedimentary materials; the anorthosites, granites, monzonites, and gabbros by fusion of the sediments, and the crystalline schists by recrystallization in the solid state.[3]

The peculiar characteristics of the anorthosites are the enormous dimensions of certain anorthosite bodies, their presence exclusively among plutonic rocks and the absence of their effusive equivalents, the frequently occurring extreme coarseness of grain,

[1] F. Loewinson-Lessing, "Kritische Beiträge zur Systematik der Eruptivgesteine. IV. Ueber monotektische (ungemischte) Magmen," *Tscherm. Min. Mitt.*, XX, p. 15.

[2] N. L. Bowen, "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, Suppl. to Vol. XXIII (1915); "The Problem of the Anorthosites," *ibid.*, Vol. XXV (1919), p. 209.

[3] N. Switalsky, "The Anorthosite Rocks and the Pyroxenic Crystalline Schists of the Southwest Baikal Region," *Bull. Com. Geol. de Russie* (1915), p. 999.

and their ancient age. The Canadian, North American, South Russian(?), and African(?) anorthosites are of pre-Cambrian age, and the Norwegian are Silurian. Of course the question of age is not to be valued too highly. New data must be expected, for we must not forget that granites were formerly also considered as exclusively pre-Cambrian, while now we know not only Paleozoic but also Mesozoic, and even Cenozoic representatives of this group.

During recent years especial attention has been paid to gravitational differentiation, a phenomenon produced by the difference between the densities of the crystallizing minerals and the still liquid portion of the magma. This conception has been especially favored by Bowen and Daly.[1]

The idea of gravitational differentiation is not new, having been introduced many years ago by Darwin. I have myself made use of this idea and have applied my own considerations and qualitative experiments to it. As before, I continue to consider gravitational distribution of phenocrysts as a factor in the mechanism of crystallization and differentiation of igneous rocks and in the formation of magmatic ore bodies; but I must confess that sometimes the significance of this factor is valued much too highly, and the limits of its application are made too broad. In order to prove this assertion and to show to what degree this factor is considered applicable by the writer, let us see briefly how different authors have applied the factor of gravitative adjustment of crystals to the theory of differentiation.

According to Sartorius von Waltershausen, even during the period of the formation of the earth's crust the liquid mass was split into layers of different densities, so that the deeper layers consisted of denser liquid masses and the upper of the lighter ones. The different volcanic centers were fed by different layers. This general speculative conception is rather far from the phenomenon of differentiation and cannot explain in a satisfactory way the diversity of volcanoes and lavas. It is useless to enter here into further details of this hypothesis.

Gouy and Chapéron expressed the idea that in a deep layer of a solution there must be a gravitational concentration of the dis-

[1] R. Daly, *Igneous Rocks and Their Origin*, 1914.

solved salts in the lower parts. Direct experiments are wanting; the oceans do not seem to support this assertion. Should this phenomenon really exist, it would assume long periods of rest in the magma, undisturbed by convectional and other currents. Let us not further insist upon this hypothesis.

Let us now examine the remaining application of gravitative adjustment in the liquid magma, namely the gravitational distribution of the minerals during crystallization. Here again we may assume two cases: (1) the distribution, according to their densities of those minerals which are the definite components of the growing igneous rocks, i.e., the components corresponding to a full equilibrium; (2) the sinking or floating of the first products of crystallization which may issue from the dissociation of the final products. These minerals correspond to an unstable and temporary equilibrium. If they are not removed by sinking or floating, they are redissolved and replaced by those definite components from whose dissociation they were derived. This is Bowen's view. It is necessary to analyze each of these two cases separately.

1. Examples of such a gravitational distribution of phenocrysts in lavas, diabases, and nephelite syenites are well known, for instance, two facies of the Vesuvius lavas, one rich in leucite, the other in augite; the more pyroxenic and the more feldspathic facies of the Olonetz (Petrosawodsk) diabase studied by the author;[1] and the nephelite-sodalite- and nephelite-eudalite-syenites of Ussing. It is only natural to attribute to this process the melanocratic facies of certain laccoliths or intrusive sheets, the granophyric upper layer of certain gabbors, the variolitic structure of certain diabase masses, and so forth. Gravitational differentiation understood in this sense certainly really exists. More than that, I think that Schweig is right in assuming that the early crystallized minerals, sinking into the deeper parts of the magma where the temperature may be higher, can be dissolved. In this way certain components of the magma may be transported by the aid of a temporary solid phase into the deeper horizons, and finally there may result two different layers and the formation of a batholith or a laccolith con-

[1] F. Loewinson-Lessing, "The Diabase Formation of Olonetz," *Trav. d. l. Soc. d Natur. St. Petersb.*, 1888.

sisting of two different rocks. In the same way differentiation may be induced by the floating of the lighter crystals, as well during the crystallization of a liquid magma as in the process of anatexis. An old experiment of Sorby[1] is very instructive. When he fused a hornblende granite from Mount Sorrel he observed that the hornblende melted first and some of the feldspar and quartz floated.

The formation in this way of a small anorthositic or pyroxenitic facies in a gabbro body is easily conceivable. On the other hand, the formation of a large anorthosite body requires rather that the sinking of pyroxene crystals should be accompanied by their resolution in the deeper parts, until the magma is finally almost completely separated into anorthosite and pyroxenite with gabbro between them.

2. According to Bowen the magma does not contain definite minerals as these are dissociated. The first crystallized minerals, being only temporary products of this dissociation, are again dissolved and disappear if the period of crystallization is sufficiently quiet and long. So, for instance, in a magma corresponding to a certain mixture of diopside and labradorite, olivine is formed at the beginning of crystallization, and in this way a certain quantity of free silica is produced. In the later stages of crystallization the olivine is again dissolved and, combining with the silica, crystallizes at last as diopside. But if the olivine, formed at the beginning, is eliminated by sinking, the magma might fully differentiate into an olivine rock, gabbro, syenite, or even granite. This conception is based on Bowen's experiments: chilling an enstatite melt demonstrated that at the beginning of crystallization olivine was formed; when crystallization was slowly brought to an end the olivine disappeared and the whole melt crystallized as clinoenstatite. It is quite certain (see Bowen's photographs) that olivine is really formed in these conditions from an enstatite melt and that it tends to concentrate in the lower parts of the crucible. But, in conceding this, we are nevertheless very far from concluding that this process is realized on a large scale in the earth's crust, and that a basaltic (gabbroid) magma will split into dunite, pyroxenite, gabbro, syenite, and granite. In order to support such a conclusion, we have to

[1] H. Sorby, *Proc. Geol. a. Polytechn. Soc. W. Yorkshire*, Vol. IV (1863), p. 302.

admit that the olivine, which is formed at the beginning of crystallization, really sinks, that this sinking is not counterbalanced by currents and movements of the magma, that the sunken crystals are not dissolved, that the deeper horizons of the magma have not a higher temperature, that the crystals sink to the bottom, that there is a bottom, that the crystallization is going on very fast, and so on.

And even if all these suppositions can be confirmed, the result of such a differentiation would be very small, as will be shown below by a series of calculations. Those minerals which can be fixed by chilling do not correspond to the final equilibrium, as is illustrated by certain alloys of metals, which when chilled show components and structures not formed in these alloys when normally crystallized. Rankin has also found in the system CaO–Al_2O_3–SiO_2 combinations which do not occur in natural rocks, but no one would therefore conclude that these combinations must also occur in the igneous rocks. The conditions of crystallization, the rate of cooling, and the admixtures are evidently different in the two cases. Since the relatively simple mixtures of chemically pure components used in the laboratory and the complex natural magmas are essentially different, deductions from laboratory experiments with simple mixtures should be applied very cautiously and with certain restrictions to the very complex natural magmas. So, for instance Bowen states several times that spinels must crystallize from a basaltic magma, but we know that basalts do not contain spinels, neither is there clinoenstatite in the igneous rocks. The conditions of crystallization of a simplified "haplobasalt" and a natural basalt are different. Not only is the composition of the latter much more complex, but the gaseous components of the magma, the mineralizers, those ingredients whose importance is now so often noted, must be considered. Experimental laboratory work is certainly very important for the problems of petrogenesis, but we must not forget that our experiments are performed with simplified mixtures and in simplified conditions. Let us not repeat the mistake of Mohr who affirmed that a simple experiment in a crucible was sufficient to refute all the theories of the plutonists. Let us continue the experiments with simple mixtures of chemically pure compounds,

but let us, at the same time, study the crystallization of melted mixtures of natural minerals and of fused igneous rocks.

Bowen gives two points as special evidence for gravitational differentiation: (1) those intrustive sheets whose lower part consists of gabbro (diabase) and the upper of granite (granophyre); (2) the connection of nephelite syenites with granites (he admits that the former overlie the latter).

1. Examples of the first case are well known. The fact itself is beyond doubt, but the question lies in its interpretation. Every author of a general theory of differentiation makes use of these facts to support his own views, and it is therefore easy to see how subjective the interpretations become. A very instructive example is afforded by the sills of the Purcell Mountains. While for Bowen they are a confirmation of his view that the granite did not come from a distinct magma but was derived from the basaltic magma which is the one and only mother-magma of all igneous rocks, for Daly the same intrusive bodies illustrate his eclectic hypothesis, of a syntexis of the basaltic magma with quartzite, followed by differentiation. Bowen asserts that the granites are everywhere underlain by granodiorites, diorites, and gabbros, and that these rocks can be seen wherever the granites are cut through by denudation. He says further that the thickness of the granite layer does not exceed from 10 per cent to 15 per cent of the whole intrusive body. Where are the proofs for such assertions, and how can they be brought into agreement with the fact that the dimensions of granite bodies exceed by far those of other intrusive rocks?

2. The frequent, or perhaps even constant (?), association of nephelite syenites with granites has been mentioned by Daly, and this is really a very frequent combination, but there are no proofs that nephelite syenites always overlie granites.

As already mentioned, the theory of the origin of the anorthosites (and other monomineral igneous rocks) by the accumulation of solid crystals, and the denial of their existence in the liquid state, is founded on the following geological and petrographical data: (1) protoclastic structure, (2) lack of dikes, (3) lack of effusive equivalents, (4) absence of mineralizers, (5) the forms of the rock bodies and their stratigraphical relations.

Let us examine each of these considerations separately.

1. Protoclastic structure is not characteristic of all anorthosites (see those of Kiev and the Baikal). This structure can be explained in certain cases by the action of mineralizers (cf. my considerations on the origin and the effect of zoisite in the anorthosites of Syysertsk in the Oural Mountains).[1] Furthermore protoclastic structure is wanting in pyroxenites and dunites, these latter being characterized by a special structure, indicative of the process I call *magmatic autocatalysis*.

2. Should it really be proved that the monomineral igneous rocks do not occur in dikes, this fact by itself would not be a sufficient proof against their existence in the liquid state. The great viscosity of such simple magmas is a sufficient cause for their being incapable of forming small intrusions. But the absence of dikes in the group of the monomineral rocks is not at all an irrefutable statement, for pyroxenites and dunites often occur in this form. Rosenbusch and Daly even assume that the dike form is usual for pyroxenites. Of course Rosenbusch (*Elemente der Gesteinslehre*) is not correct in assuming that pyroxenites and peridotites occur only in dikes; the large intrusive masses of pyroxenites in the Blue Mountains near Barantcha (Oural),[2] the pyroxenites and dunites of the Denejkin Kamen,[3] and other localities in the Oural Mountains are in contradiction with this assertion.

Certain feldspathic rocks occur also in the dike form, for example, the albitites. In the region of the Canadian anorthosites Adams cites dikes. On the other hand, we may ask: Do gabbros (except beerbachite and gabbroporphyrite) or nephelite syenite often occur in this form?

[1] F. Loewinson-Lessing, "On the Most Southern Deposit of Platinum in the Oural," *Annales de l'Inst. Polytechn. St. Petersb.*, Vol. XIII (1910).

[2] Th. Tschernyschew, "Le Chemin de fer dans les Limites les districts miniers de Taguil et de Goroblagadat," *Guide des Exeurs., Congr. Geol. St. Petersburg*, 1897.

F. Loewinson-Lessing, "A New Locality of Platinum Deposits (in the Blue Mountains, near Barantcha, Oural)." *Annals l'Inst. Polytechn. St. Petersburg.* 1909. Vol. XI.

[3] F. Loewinson-Lessing, "Geologische Skizze der Besitzung Jushno-Saasersk und des Berges Denejkin Kamen im nördl. Ural." *Trav. d.l. Soc.d. Natur. St. Petersburg*, 1900. In this monograph I have described and figured a series of very manifold banded gabbros. Grout does not cite me in his paper on banded structures as he evidently does not know my book.

3. The lack of effusive equivalents of the anorthosites and other monomineral igneous rocks is quite a natural consequence of their great viscosity and their consequent inability to reach the earth's surface in the liquid state. I have previously pointed to that conclusion. Bowen refutes these considerations but without any arguments.

4. The mineralizers, and those minerals which are to be referred to their action, are in general very rare in basic rocks. In many gabbros they are quite absent. Meantime we may remember that the zoisite mentioned above in certain anorthosites from the Oural, and the primary serpentinization of the dunites are to be referred to the action of mineralizers.

5. The stratigraphical relations of the anorthosites argue for their igneous and not for their sedimentary or metamorphic origin. Their igneous origin is demonstrated by their intimate connection with the rocks of the gabbro group and through these with syenites by the anorthositic (and pyroxenitic) facies of the banded gabbros, by several features illustrating their intrusion into the neighboring rocks, and by contact metamorphic actions, as for instance, around the big Canadian anorthosite bodies. But it is not enough to state their intrusive origin in such general terms, for there are in the geological literature two different interpretations of the anorthosites, both, as already stated, relying on the theory of intrusion. It is necessary, therefore, to analyze more closely the stratigraphical relations in order to see whether they support the views of most writers or those of Bowen.

Adams[1] states with reference to the Morin laccolith: "Fassen wir noch einmal zusammen, so haben wir in diesem Gebiet eine grosse intrusive Masse von Anorthosit, welche die Grenville Stufe durchbricht, grosse Gneissblöcke einschliesst, Apophysen in die umgebenden Gesteine entsendet und an vielen Stellen, wie es scheint, von einem eigenartigen Contactproduct begleitet wird." Especially important seem to me the contact phenomena and the small intrusive sheets of anorthosite in the gneiss. Daly (p. 331) agrees with Adams, and says, in reference to the Morin laccolith and several intrusive bodies of gabbro and anorthosite in the Haliburton-

[1] F. Adams, *op. cit.*, p. 433.

Hastings region, that the zones of contact coincide with the cleavage surfaces of the gneisses, limestones, and other rocks, and since the cleavage is parallel to the stratification planes, the metamorphic zones argue for the laccolithic and not batholithic character of these bodies. Bowen's mention of the local occurrence of perthitic feldspar is hardly an argument for the hypothesis that the anorthosite was covered by syenite, that both are derived from a basaltic magma, and that the anorthosite is a sheetlike mass, like the intrusive mass of the Adirondacks. Of course, in stating that the Adirondak massive is a sheetlike body consisting of anorthosite at the bottom and syenite at the top (both rocks resulting from a differentiation *in situ* of a basaltic mother-magma), Bowen is cautious and considers this interpretation a conditional one: "And again, the writer's interpretation of the igneous mass as sheetlike is offered merely because of the difficulties of picturing the general relation otherwise."[1] At the same time he mentions xenoliths of Grenville rock in the anorthosite, a feature suggesting the intrusive character of the anorthosites, and gives examples of assimilation of the covering rock by the syenite, etc. All these data show that the stratigraphical features are not conclusive for Bowen's views. And furthermore, it is rather doubtful whether the accumulation of labradorite crystals at the bottom and the separation of a syenitic liquid at the top do agree with their respective densities at the temperatures existing during the stage of crystallization when this differentiation was going on.

The connection of anorthosite with syenites in the Morin and Andirondack bodies is conspicuous, but their genetic relations are not sufficiently evident. Cushing considers the Adirondack syenite as younger than the anorthosite, the syenite sending apophyses into the anorthosite—a statement decidedly invalidating Bowen's interpretations.

The other labradorite regions do not afford such stratigraphical data as could be made use of for sustaining this or that interpretation. I could find such data neither in Kolderup's[2] writings on the

[1] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, Vol. XXV (1917), p. 226.

[2] K. Kolderup, "Die Labradorfelse des westlichen Norwegens. Ia, II," *Bergens Mus. Aarbog*, Vol. I (1896; Vol. V (1903), No. 12.

Norwegian labradoritites, nor in Tarassenko's[1] monograph on the labradoritites of Kiev.

The problem of the anorthosites is not exhausted by an interpretation of the anorthositic bodies. There still remain the anorthositic bands in the banded gabbros of Scotland and the Denejkin Kamen (the latter evidently unknown to Bowen). To these bands the conception of an accumulation of solid crystals is evidently not applicable, and the feldspathic, pyroxenitic, and magnetitic (titanomagnetite), as well as the leucocratic and melanocratic bands, must without doubt be considered as produced by differentiation from the liquid state. The writer and Harker have spoken of liquid immiscibility; I have further advocated the possibility of liquation in consequence of assimilation; and we can invoke other constituents coming into the magma during the process of assimilation, or the absorption of gases that can produce insolubility of a certain component and be therefore the cause of its precipitation, like alcohol precipitating some substance form an aqueous solution. All of these suppositions are only conjectures. Experimental data are needed; but there are certainly data favoring the hypothesis of magmatic differentiation, and Bowen's hypothesis is not applicable to the banded gabbros.

In the Denejkin Kamen the ultrabasic rocks occur as small veins and dikes in the gabbro. Their solidification was subsequent to the consolidation of the gabbro and not the reverse as required by Bowen's scheme. In Quebec (Chibougamau) according to Daly, the hornblendite, pyroxenite and dunite cut the gabbro in dikes.

Vogt, as is well known, has applied the eutectic scheme to the interpretation of monomineral rocks. Bowen, on the contrary, considers this scheme as inapplicable to igneous rocks because of the widespread occurrence of solid solution. I think there is a misunderstanding. Solid solutions and isomorphism are confined to limited mineral groups, but the minerals of different groups, in spite of being solid solutions, may be in eutectic relations. Conceding to Bowen that it is not correct to speak of a eutectic mixture of diopside and plagioclase, since the different plagioclases have

[1] W. Tarassenko, "The Rocks of the Gabbro Family in the Radomysl and Shitomir Districts of the Governm. of Kiev," *Mem. Soc. Natur. Kijev.*, Vol. XV (1896), pp. 1–347.

different fusion points, we can certainly speak of diopside-labradorite (of a definite composition) eutectics, diopside-anorthite-eutectics, etc. In certain cases the eutectic scheme is doubtless to be upheld. For the rocks of granitoporphyric (holocrystalline-porphyritic) texture I consider the eutectic rule as the leading factor in the formation of phenocrysts. For instance, by measurements with the Hirschwald ocular I have found that in diorite-porphyrite the phenocrysts belong either to amphibole or to plagioclase depending upon the predominance of the one or the other respectively over a certain proportion, which is to be considered as the eutectic mixture, quite as with alloys of metals or salts.[1]

Finally we must not omit the paragenetic relations of the great anorthositic and pyroxenitic regions. The anorthosites of Canada, Norway, and southwest Russia are connected with gabbro, norites, and syenites. They belong to that type of the gabbro formation which is united by intermediate members with syenites, and which is not accompanied by pyroxenites and dunites. On the other side the pyroxenites (Oural, America) and dunite are connected with a more basic type of the gabbro group. In the Oural they are accompanied by various ultrabasic types. There may be a certain legality in these connections, but it certainly would be a forced explanation should we say that in the Oural formations the anorthosites were destroyed by denudation, and that in Canada, Kiev, etc., the denudation has not yet reached the pyroxenites.

In regard to the paragenetic relations it is not to be lost sight of that the pyroxenite and dunite occur in connection with gabbros which contain the same minerals; alkaline pyroxenites are connected with alkaline rocks, albitites, and andesine feldspatholites with dioritic rocks, and labradoritites with gabbros. It is shown by these peculiarities of paragenesis that the monomineral facies is always formed by those minerals which are the characteristic components of the corresponding mixed rock; that the differentiation proceeds by the transfer of these minerals, which crystallized from the original magma (Brögger and myself), and not by the transfer

[1] F. Loewinson-Lessing and S. Žemčujny, "Porphyrartige Struktur und Eutektik," *Verhandl. Russ. Miner. Ges.*, 1906. (Experiments with salts and metallographic photograms of them.)

of temporary minerals unstable during the later stages of the crystallization of such a magma.

Let us now make several calculations which will show that even if we lay aside all the foregoing considerations and take Bowen's viewpoint, it is impossible to expect such effective differentiation as is assumed by Bowen from his experiments. Bowen studied the crystallization of a gabbroic magma consisting of 50 per cent labradorite (Ab_1An_1) and 50 per cent diopside. We will examine a magma of nearly this composition but containing also magnetite, as it usually does.

Let us take two mixtures:

I. 6 parts diopside: molecular weight $216 \times 6 = 1296$, or 41.3 per cent (in molecular percentages).
2 parts labradorite: $804 \times 2 = 1608$, or 51.2 per cent.
1 part magnetite: 232, or 7.4 per cent.
(The sum of the molecular weights is 3156; the total of molecular percentages 99.9).

II. A similar mixture but containing less magnetite, namely,

	Per cent
Diopside	42.3
Labradorite	52.4
Magnetite	5

We begin with the second mixture and examine two cases:

a) If two-thirds of the enstatitic silicate of our magma splits into olivine and free silica there will remain a pyroxene 2 ($MgO \cdot 3\ CaO \cdot 4\ SiO_2$), and we will have olivine $2(2\ MgO \cdot SiO_2) + 2\ SiO_2$. The free silica will be combined with the Fe_3O_4, i.e., to 2 FeO, and consequently there will be no formation of quartz.

b) If we assume the improbable case that the whole mass of the magnesian metasilicate will split and the rest will be 6 $CaSiO_3$ there will be 3 $(2\ MgO \cdot SiO_2) + 3\ SiO_2$, and after the neutralization of 2 SiO_2 by the ferrous oxide the remaining free silica can give 1.91 per cent of quartz.

We take now the first mixture (I). In the same conditions as already stated, even if the whole mass of the magnesian metasilicate splits, there will be no free silica.

We can admit a third case (III), namely, a magma devoid of magnetite, or we may suppose that the free silica will not combine with the magnetite. This will give us SiO_2 3 or 5 per cent of free silica.

Therefore, even if we admit conditions most unnatural and most unfavorable for Bowen's critics, a basaltic magma will either give no free silica at all, or will give only such a small amount that at best we can expect the formation of a quartz gabbro, poor in quartz, but never of granite or quartz-diorite.

Besides this it ought to be noted that Bowen[1] considers clinoenstatite as the only stable form under conditions of slow crystallization. During slow cooling full equilibrium is established, and only under conditions of artificial chilling can the minerals of the incomplete equilibrium stage (forsterite, enstatite, cristobalite) be fixed. The conditions of crystallization of the intrusive magma are those bringing it to full equilibrium.

And again, Bowen[2] tells us that a mixture of 98 per cent $MgSiO^3$ and 2 per cent SiO^2 will give forsterite and silica; but if there is 2.5 per cent or 3 per cent of silica, enstatite will be formed—a statement invalidating all presumptions on the formation of olivine and free silica from a basaltic magma.

Let us now make another calculation based on the specific gravities. In Daly's *Igneous Rocks* (p. 202) we find the specific gravities of gabbro, syenite, quartz, diorite, and granite at the temperatures of 20° C., 1000° C., 1200° C., and 1300° C., in the solid state and when molten. The specific gravity of crystalline labradorite is 2.689; when molten to glass it shows an expansion of nearly 7 per cent—specific gravity 2.525. Heated to 1000°–1300°, if still solid, the increase of volume if only equal to 3 per cent, will give a specific gravity of 2.609. Now, comparing these figures with the specific gravity of the liquid gabbro it is easy to see that the labradorite will sink only in a gabbro with a specific gravity of 2.80 (if molten 2.57–2.53); in all other cases the labradorite will float, especially if we take into consideration that the average density of gabbro is 2.933–2.975. I can easily conceive that during the crystallization of a gabbroic magma there will be a tendency toward

[1] N. Bowen, *Amer. Jour. Sci.*, CLXXXVIII (1914), p. 237.

[2] *Amer. Jour. Sci.* (1914), p. 487.

the formation of a melanocratic facies in the lower part and a leucocratic in the upper. Possibly there may really be formed at the bottom (if there is a bottom) a sheet of pyroxenite corresponding to the early stage of crystallization, when this mineral alone is formed. Perhaps somewhere in the upper part or at some other horizon a sheet of labradorite may arise. But that is not the process advocated by Bowen.

Let us follow him. The crystallization begins with diopside, and later but while diopside is still forming, labradorite begins to crystallize. If before the crystallization of the feldspar two-thirds of the diopside and all of the magnetite have already crystallized, there will remain a leucocratic facies consisting of 80 per cent labradorite and 20 per cent diopside. But Bowen's scheme is somewhat different. When the feldspar begins to crystallize, it is not labradorite but the more basic bytownite, Ab_1An_4, that is formed. The specific gravity of this feldspar, according to Bowen himself, is very near to that of the liquid, so that these crystals would not sink in the original liquid. They do sink because the liquid after the crystallization of a certain amount of diopside, becomes of the composition of a syenite, and gets lighter. Indeed, if after the crystallization of two-thirds of the diopside, bytownite, Ab_1An_4, is formed, presumably in such quantity that one-half of the anorthite contained in the primordial magma has been spent, there will remain a mixture of nearly 50 per cent albite, 26 per cent anorthite, and 24 per cent diopside, or a syenite of the following composition:

	Per cent
SiO_2	62
Al_2O_3	19.5
MgO	2.6
CaO	7.2
Na_2O	8.5
	99.8

In this way, as we see, a soda syenite is formed, and in the later stages of Bowen's scheme a soda granite may arise. It must be noted that the syenites which are associated with anorthosites are not soda syenites but ordinary potash syenites.[1] Bytownite must

[1] The "mangerites" of Kolderup, which accompany the Norwegian labradorites and stand near to the nordmarkites, contain nearly equal quantities of soda and potash (5.51 per cent Na_2O and 6.57 per cent K_2O).

sink in this syenitic liquid. But we must not forget that this bytownite is, according to Bowen, only a temporary component. In the following stages of crystallization by reaction with the liquid, the albite is extracted, and gradually the feldspar is transformed into labradorite, representing the final product of crystallization. If so, the liquid will again change from syenitic to leucocratic-gabbroid, and the sunken crystals will once more float.

The foregoing considerations therefore, lead to two possibilities: (1) In consequence of the sinking and subsequent floating of the crystals while the diopside continues to crystallize, and in consequence of vertical and other currents that must arise under these circumstances, the crystals of diopside and labradorite will be mixed and no anorthosite will be formed. (2) If the crystallization proceeds in the manner assumed in the first case, namely if diopside and labradorite crystallize directly, there will be a tendency toward sinking and floating of the minerals. This tendency can produce a complete separation of the two minerals only in the case of mingling movements (as is illustrated in the separation of minerals in heavy liquids). Such movements being absent and the liquid being quiet, there can arise melanocratic and leucocratic facies with intermediate members, but of course not a syenite nor a granite.

Summary.—Summarizing all that has been said above, we must concede that the problem of the anorthosites and other monomineral igneous rocks is not yet completely solved. It must be conceded that in certain cases several factors, to which different authors refer, may possibly or actually take part in the formation of these rocks; but every attempt to put forward only one of these factors to the exclusion of the others, gives proof of exclusiveness and insufficiency. Indeed, such rocks as gabbros with anorthositic or pyroxenitic bands cannot be understood without admitting the existence of anorthosite and pyroxenite in the liquid state. But I am far from asserting that the only possible explanation is the hypothesis of liquid immiscibility, and that this is applicable to all forms of anorthositic rocks. And again, the possibility of the separation of crystals of pyroxene and labradorite from a gabbroic magma is sufficiently illustrated by the analogous phenomenon in porphyritic lavas, and is corroborated by their respective specific

gravities. But if we deduce from this that the gravitational distribution of crystals and crystallization-differentiation solves the whole problem of the anorthosites, we will meet with difficulties in the course of the crystallization, and especially in the fact that monomineral rocks represent relatively rare facies, while normal undifferentiated gabbro-noritic rocks are by far more frequent. Why, we must ask, does crystallization-differentiation not always lead to these final products of gravitative liquation? Bowen's experimental researches and his deductions from them, give inductions which in many points are theoretically correct for a theory of the crystallization of a gabbroic magma. But we have seen above that Bowen's scheme, based on the gravitational accumulation of crystals and operating with temporary minerals which disappear in the later stages of the crystallization of the magma, meets with several difficulties of theoretical and calculative character. I think, therefore, it is more correct to acknowledge that the problem of the monomineral igneous rocks and in particular, of the anorthosites, is not yet solved. It were better for this problem to remain an unsolved riddle to stimulate further investigations than to become, if unilaterally solved, a possible source of dogmatism.

PETROGRAD
May, 1921

THE GROWTH OF STALAGMITES AND STALACTITES[1]

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OUTLINE

INTRODUCTION

The methods now in use for evaluating recent geological and remote archeological periods, in terms of years, are not numerous; therefore the addition of another method, even though it is only

[1] This paper received the Morrison prize of the New York Academy of Science.

an approximation, may be useful. A number of investigators during the last century have considered the question of the rate of stalagmitic growth as an aid in archeological chronology, but careful observations on different stalagmites gave such widely varying results that the observers were discouraged. This is not surprising since they expected to secure uniformity in results from stalagmites grown under very diverse conditions.

HISTORICAL

In 1874, W. Boyd Dawkins examined certain lime deposits in Ingleborough Cave, Devonshire, and came to the conclusion, "It may fairly be concluded, that the thickness of layers of stalagmite cannot be used as an argument in support of the remote age of the strata below."[1]

He repeated this opinion later.[2] In 1896, Horace C. Hovey, in writing of the stalagmites in Mammoth Cave, says, "Hence any estimate as to their age in years is idle and fruitless. It is only certain that they are *very old*."[3] George Byron Gordon[4] lists and discusses the factors affecting lime deposition, and gave the opinion, "It is evident, therefore, that the presence of a few inches of stalagmite is of little value in determining lapse of time." Charles Peabody and W. K. Moorehead,[5] in 1904, said, "Unfortunately absolutely nothing can here be adduced with precision," in referring to stalagmitic growth. Martel,[6] in 1900, said of stalagmites, "that their height cannot be considered in any way a contributing element to chronological calculations." Oliver Cummings Farrington,[7] in 1901, foresaw the possibility of estimating the age of some stalagmites.

[1] W. Boyd Dawkins (1874), pp. 38–41.

[2] W. Boyd Dawkins, *Quarterly Journal of the Geological Society*, LX (1904), 374.

[3] Horace C. Hovey, *Celebrated American Caverns* (1896), pp. 94, 95.

[4] "Caverns of Copan" (1896–1902), Peabody Museum, Harvard University, *Memoirs*, I, 11, 12, of the article on pp. 147, 148, of the volume.

[5] "Exploration of Jacob's Cavern," *Bull. No. 1, Dept. of Archaeology, Phillips Academy*, Andover, Massachusetts.

[6] *La Speleologie ou Science des Cavernes*, Paris (1900), pp. 102, 103.

[7] "Observations on Indiana Caves," *Field Columbian Museum, Pub.* 53, *Geol. Series*, I (1901), No. 8.

FACTORS AFFECTING STALACTITIC DEPOSITION AFTER THE LIME SOLUTION HAS REACHED THE CAVE

1. Drip. Size of feeders.[1]

2. Rate of evaporation within the cave.[2] Air circulation, temperature, and humidity.

3. Diverting bodies under the drip.[3] Important only if relatively large in comparison with lime deposition.

4. Shifting of drip.[4] Complicates calculation of resultant mass. Not important.

5. Surface tension. Affects pendant drop.

6. Capillarity. One phase of surface tension which tends to hold solution in stalactitic tube.

7. Gravity.

The term "evaporation" includes the precipitation of the lime as basic carbonate by the removal of the carbonic acid from the solution, as well as the removal of the water.

A dripping stalactite means more solution than the evaporation conditions will handle. A small drip and rapid evaporation may mean no stalagmite and a rapid-growing stalactite. A rapid drip and poor evaporation may mean no stalactite but a slow-growing stalagmite[5] with large diameter. Small drip and poor evaporation gives slower growth and smaller diameter to the stalagmite.

STALACTITES

GROWTH OF STALACTITES

A stalactite forms as a slender tube,[6] which increases in diameter until the drip and evaporation reach equilibrium. The increase in diameter is effected partly by the creeping of the lime solution up over the rim of the stalactite and partly by the lime solution percolating from the inside of the tube outward through small

[1] Charles Peabody and W. K. Moorehead, *loc. cit.*

[2] George Byron Gordon, *loc. cit.*

[3] Charles Peabody and W. K. Moorehead, *loc. cit.*

[4] *Ibid.*

[5] *Ibid.*, p. 257.

[6] Chamberlain and Salisbury, *Geology*, Vol. I, *Processes* (2d ed. revised, 1909), p. 229.

channels in the stalactite wall. After drip-evaporation equilibrium is attained, the stalactite continues to grow *symmetrically*, (with uniform diameter) in the vertical direction, *unless conditions change*.

The removal of the carbonic acid from the pendant drop of lime solution causes the precipitation of the basic carbonate of lime as a thin, translucent film on the surface of the drop. If evaporation is good, this film is repeatedly broken and the pieces go spinning up to the rim of the tube—the drop is "alive." This spinning motion is due to surface tension and also to the fact that the down-flowing current is at the center of the drop and the up-flowing current at the periphery. Figure 3 shows a drop that is "alive"—good evaporation. Figure 5 shows a drop that is "dead"—poor evaporation.

Preceding the breaking away of the drop, there is a periodic, vertical oscillation which increases in frequency and amplitude until the actual break occurs.

EXAMPLES OF GROWING STALACTITES

Stalactites are growing under known evaporation conditions at the Experimental Mine of the United States Bureau of Mines, near Bruceton, Pennsylvania, on the concreted roof. Experimental coal-dust explosions are conducted in the mine during fall and winter, when the mine is dry, and high air is used to purge the mine of smoke and dust. The parts of the stalactites which grow during this period are blackened. This allows the rate of growth and the age of the stalactites to be closely determined. Also, certain of the stalactites are growing in the aircourse which is subject to violent explosions when the coal-dust work is under way. They are therefore no older than January 8, 1921, when the last explosion experiment was made. Unsymmetrical stalactite No. 2 grew in a gallery which was not completed until September 9, 1921. All these are rapid-growing stalactites of shell-like tube form, 0.4 to 0.5 cm. in outside diameter for the small part and about 1.0 to 1.2 cm. for the large part. The walls are about 0.02 cm. thick and are studded on the inside with small excrescences about 0.05 to 0.08 cm. thick. The rates of growth of the stalactites are given in Table I.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIGS. 1-5: Fig. 1.—Unsymmetrical stalactite No. 1; Fig. 2.—Unsymmetrical stalactite No. 1, enlarged about 6 diameters; Fig. 3.—Symmetrical stalactite No. 1; Fig. 4.—Unsymmetrical stalactite No. 2; Fig. 5.—Unsymmetrical stalactite No. 2, enlarged about 6 diameters.

TABLE I

RATE OF GROWTH OF EXPERIMENTAL MINE STALACTITES

Stalactite	Rate of Growth	Rate of Drip
	cm. per month	
Symmetrical No. 1	0.76	One drop every 21.8 minutes
Symmetrical No. 2	0.74	One drop every 81.0 minutes
Symmetrical No. 3	0.10	One drop every 5 seconds
Symmetrical No. 4	0.40	One drop every 3 seconds
Symmetrical No. 5	0.73	One drop every 46.2 minutes
Unsymmetrical No. 1	0.76	One drop every 53.3 minutes
Unsymmetrical No. 2	1.44	One drop every 13.8 minutes
Unsymmetrical No. 3	0.73	One drop every 18.8 minutes
Unsymmetrical No. 4	0.80	One drop every 6.1 minutes

EFFECT OF THE VARIOUS FACTORS AFFECTING THEIR GROWTH

These stalactites are shown as follows: unsymmetrical stalactite No. 1, Figure 1, enlarged about 6 diameters, Figure 2; symmetrical stalactite No. 1, Figure 3; unsymmetrical stalactite No. 2, Figure 4, enlarged about 6 diameters, Figure 5; unsymmetrical stalactite

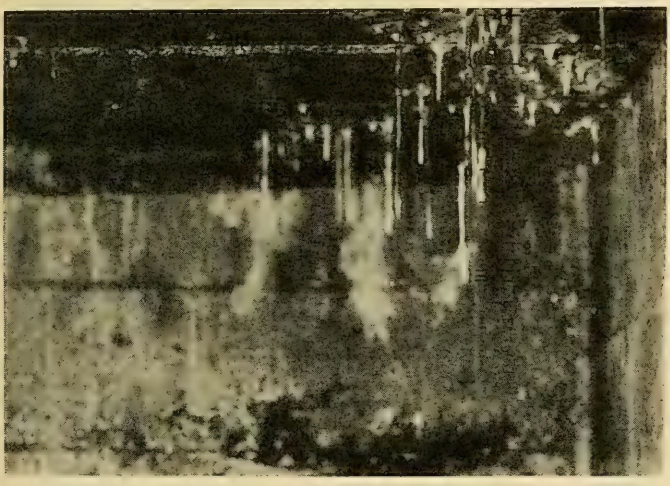

FIG. 6.—Unsymmetrical stalactite No. 3

No. 3, Figure 6; unsymmetrical stalactite No. 4 and symmetrical stalactite Nos. 2, 3, 4, and 5, Figures 7 and 8, unsymmetrical stalactite No. 2 grew on green concrete, all the others on concrete from three to eleven years old. Carbonic-acid charged water evidently abstracts lime more easily from young concrete. Con-

centration then increases vertical growth. The only ones with rapid drips are symmetrical stalactites Nos. 3 and 4, which show that a rapid drip means a show vertical growth. The concentration of

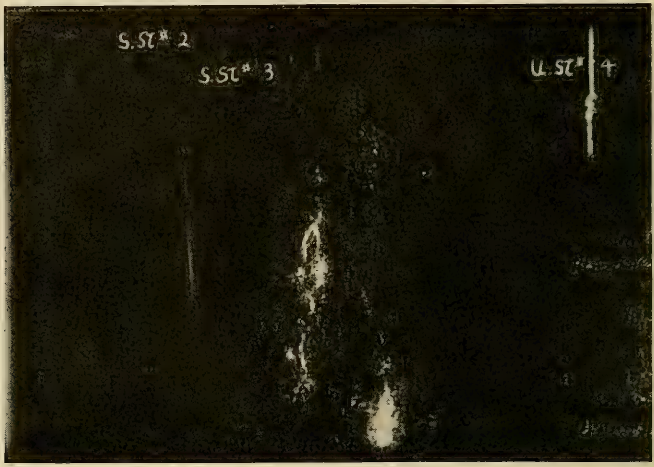

FIG. 7.—Symmetrical stalactites Nos. 2 and 3 and unsymmetrical stalactite No. 4

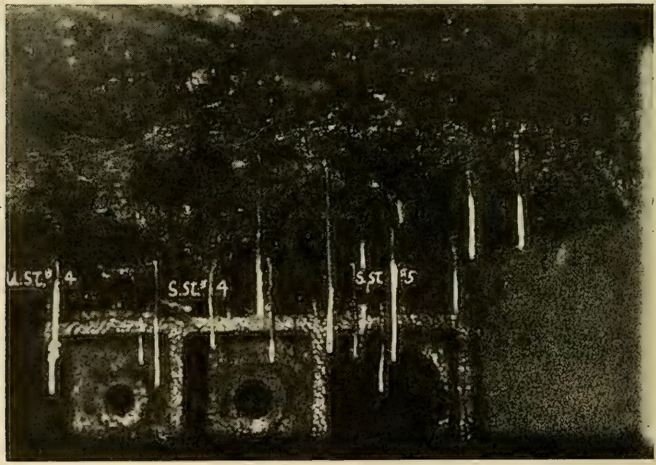

FIG. 8.—Unsymmetrical stalactite No. 4 and symmetrical stalactites Nos. 4 and 5

symmetrical stalactite No. 4 is greater than that of symmetrical stalactite No. 3.

The diameters of all the symmetrical and the small diameters of the unsymmetrical stalactites are about equal. Evaporation

conditions are also about equal. A certain concentration evidently is in equilibrium with the evaporation. When evaporation conditions are lowered, the lime solution has a greater time interval before precipitation after contact with the air. This allows the solution, providing the drip is not too rapid, to be spread out by capillary attraction before all the lime is precipitated. If the concentration is sufficiently high so that part of the lime remains unprecipitated after the solution is spread out, this residual lime is then precipitated over the enlarged diameter. The larger diameter means the effect of lowered evaporation upon a drip of fairly high concentration.

Rapid vertical growth is favored by high air circulation, high temperature, and high concentration, and is opposed by rapid drip and high humidity.

Large diameter is favored by low air circulation, low temperature, high concentration, and high humidity, and opposed by a rapid drip (Fig. 14).

Surface tension and capillarity greatly affect stalactitic growth, but stalagmitic growth hardly at all on account of the larger surface (necessary to evaporate the water received, which cannot drip away as in the case of a stalactite) with the consequent decrease of surface energy per sq. cm. Also, in the case of stalagmites, gravity works against surface tension and is therefore minimized.

The more variables that can be eliminated, the greater the chance for the solution of such a complex problem. The work on the rate of growth will hereafter be confined to stalagmites which are affected by rate of drip, air circulation, relative humidity, temperature, and concentration.

STALAGMITES

TABLE II

Experimental Mine Stalagmites Studied

Stalagmite	Corresponding Stalactite	Drip	Circumference	Rate of Vertical Growth
		Sec.	m	cm. per year
No. 2	S.St. No. 3	3	.22	.70
No. 3	U.St. No. 4	368	.11	.60
No. 4	S.St. No. 4	5	.22	.60

These three stalagmites, among others, are shown in Figures 9 and 10, and in three-quarters view in Figure 11. Vertical and

FIG. 9.—Stalagmites Nos. 1, 2, and 3

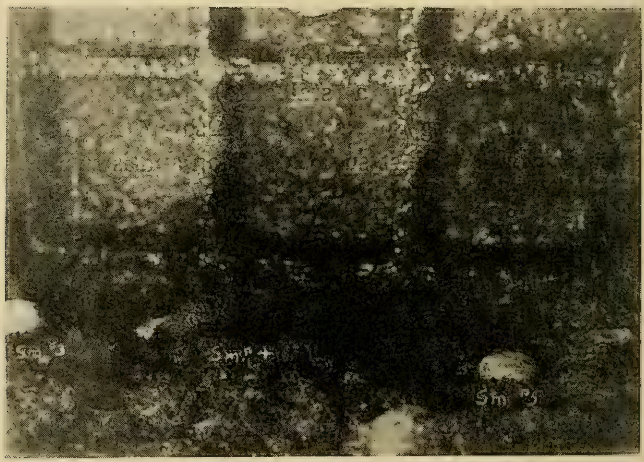

FIG. 10.—Stalagmites Nos. 3, 4, and 5

cross-sections of the three stalagmites studied are shown in Figures 12 and 13. The rate of growth is obtained from the "coal-dust bands" appearing in the vertical section. The light part of stalagmite No. 3 is colored red with iron, as is its corresponding stalactite.

FIG. 11.—Stalagmites Nos. 2, 3, and 4, in three-quarters view

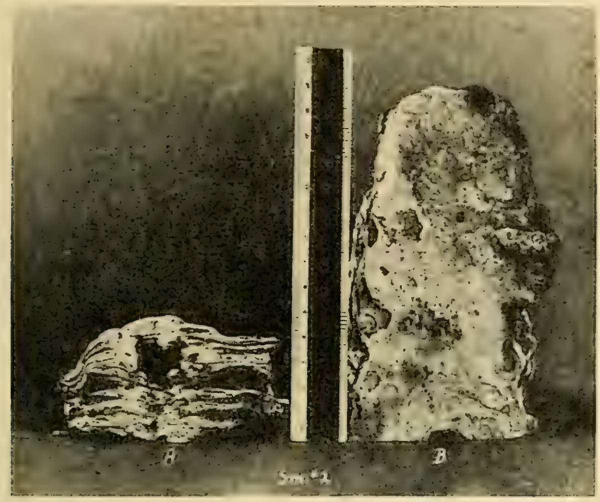

FIG. 12.—Stalagmite No. 2, vertical section and cross-section

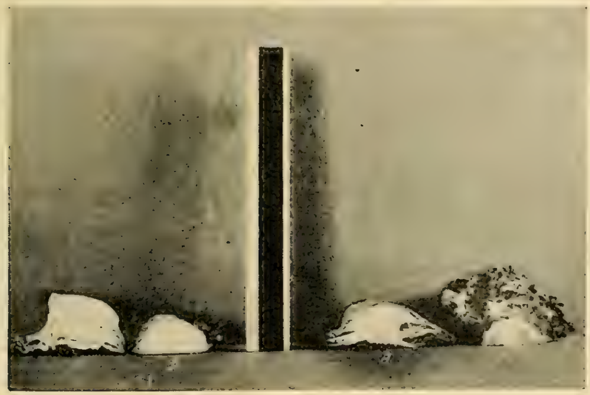

FIG. 13.—Stalagmites Nos. 3 and 4, vertical section and cross-section

EFFECT OF THE VARIOUS FACTORS UPON THE GROWTH

Approximately equal rates of vertical growth are noted for drips varying from 3 to 368 seconds, although the diameter increases with the rate of drip. The variation in concentration is very largely taken care of by the stalactite, especially in slower drips, before the solution reaches the stalagmite.

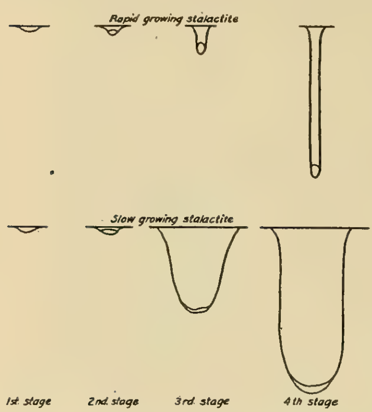

Fig. 14.—Diagrammatic outline of method of growth of stalactites.

"SPLASH CUP"

The cup at the top of some stalagmites is a "splash cup." Stalagmites Nos. 1, 2, 3, and 5 have cups of practically the same diameter, although of varying drip, and are about 40 cm. below their stalactites. The greater the distance of fall, the greater the diameter of the "splash cup." Symmetrical No. 4 has no cup on account of its greater concentration of drip. The cup of symmetrical No. 2 is deep, while the other cups are shallow; also its rate of drip is more rapid. The depth of the "splash cup" is increased by high evaporation, low concentration, and rapid drip.

THE MODE OF ORIGIN

At the start, a stalagmite is limited to a circle bounded by the splash of the drops hitting the floor. Good evaporation and rapid drip cause the formation of a saucer at the limit of the circle. The bottom of the saucer slowly rises as lime is deposited in it, and the excess solution cascades down over the rim and down the sloping sides of the stalagmite until such a diameter and convex surface are realized that the resulting evaporation surface will be just sufficient to evaporate the solution it receives. The stalagmite will now continue to grow vertically in a *symmetrical form unless conditions change.*

Poor evaporation and high concentration (or both) mean that the spattering drops will eventually form a small mound which will increase in height and decrease in diameter until the drip and evaporation surface is in equilibrium. It will then grow *symmetrically,* in a vertical direction, *unless conditions change* (Fig. 15).

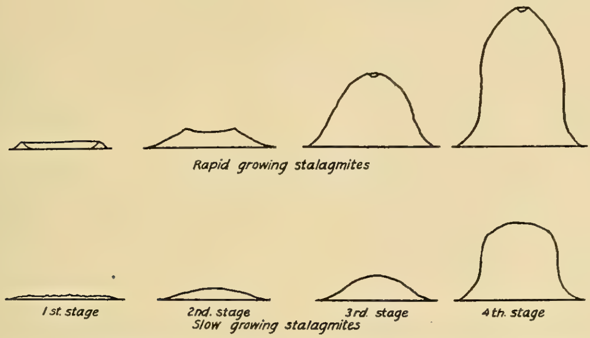

FIG. 15.—Diagrammatic sketch of method of growth of stalagmites

UNSYMMETRICAL STALAGMITES

A "mushroom" stalagmite is one in which the diameter has increased after a period of small diameter growth.

A "stool" stalagmite is a "mushroom" stalagmite in which the diameter has returned to about the same original diameter after the "mushroom" enlargement.

A "needle" stalagmite is one in which the diameter has decreased after a period of large diameter growth.

A "choked" stalagmite is one in which the diameter has returned to about the same original diameter after the "needle" effect had taken place.

The "mushroom" effect is caused either by an increase in the drip or a decrease in the conditions of evaporation. In the case of an increased drip, the slope between the original diameter and the enlarged diameter will be gentle because the vertical growth will increase slightly at the same time that the diameter increases. In the case of decreased conditions of evaporation, the slope between the original diameter and the enlarged diameter will be abrupt because the vertical growth will be decreased at the same time that the diameter is increased. If the original conditions return

again to about their previous magnitude, the stalagmite will exhibit a "stool" effect instead of a "mushroom" effect. A decrease in the drip or an increase in the evaporation conditions will cause the stalagmite to take on a "needle" form while if the conditions again return to about their original magnitude, the stalagmite will acquire a "choked" effect.

In the case of an abrupt slope between the large diameter and the small diameter (lowered conditions of evaporation), a lowered temperature is suspected because of its triple effect; decreasing the air circulation if the cave is ventilated by the thermal syphon method, reducing the vapor pressure of the lime solution, and increasing the absolute humidity. Evidence of a change in the air events of the cave will of course account for a change in the conditions of evaporation.

STALACTITIC CURTAINS

Observations on the stalactitic curtains behind symmetrical stalactites Nos. 2 and 3 Fig. 7 indicate that a slow drip, high concentration curtain will increase in thickness ("diameter") about one-fifth as rapidly as a stalagmite will grow vertically under corresponding conditions, and a rapid drip, low concentration curtain will increase in thickness about one-fortieth as fast as stalagmite will grow vertically.

SEASONAL INTERMITTENCY

Present seasonal intermittency can be ascertained by observation, and the *symmetry* of the stalagmite shows whether or not the present conditions held during its previous existence. If the stalagmite is "dead," the face will show a slight "needle" tendency, together with a corrugated or "petticoated" columnar section, similar to icicles,[1] if the drip has been seasonally intermittent.

GROWTH INDICATIONS

A sharply convex face means a rapidly growing stalagmite, and a blunt face means a slowly growing stalagmite. The deeper the "splash cup," the faster the drip, and the better the evaporation, and the wider the "splash cup," the greater the distance of fall. Absence of a "splash cup" means a high concentration.

[1] Farrington, *op. cit.*, p. 263.

CLASSIFICATION OF. STALAGMITES

TABLE III

Limits of Factors Affecting Stalagmitic Growth

Factor	Upper Limit	Lower Limit	Ratio
Drip.............	*D* Five drops per second	*d* One drop per 5 minutes	1,500 to 1
Air circulation.....	*A* 500 cu. ft. per minute	*a* $\frac{1}{2}$ cu. ft. per minute	1,000 to 1
Relative humidity..	*H* 100 per cent	*h* 2 per cent	50 to 1
Temperature	*T* 90° F.	*t* 50° F.	40 to 1
Concentration	*C* 100 per cent	*c* 10 per cent	10 to 1

There are five factors given as affecting the growth of stalagmites, and each of these factors has been assigned two limits: an upper limit and a lower limit. Starting with the drip, it is seen that there will be two general classes of stalagmites: those with a large drip and those with a small drip. Each of these two classes will be further subdivided into two more classes: a class growing under high air circulation and a class growing under low air circulation. If these four classes are further subdivided according to high and low humidity, high and low temperature, and high and low concentration, it will be found that a total of thirty-two classes or types of stalagmites are possible.

It has been found that the circumference of a stalagmite is increased by fast drip and high humidity, and decreased by high air circulation and high temperature. This may be expressed by the relation: Circumference is proportional to

$$\left(\frac{D \times H}{A \times T}\right)^{\frac{1}{2}}$$

The $\frac{1}{2}$ power is used because it is in reality the surface or area of the face of the stalagmite that is affected, and this increases as the square of the diameter.

The rate of vertical growth of a stalagmite is favored by high air circulation, high temperature, high concentration, and to a small extent by a fast drip. The only factor opposing a rapid rate of vertical growth is high humidity. It can then be stated that the vertical growth is proportional to

$$\frac{A \times T \times C \times (12 + \log D)}{H}.$$

DIVISION INTO THIRTY-TWO TYPES

Each of the thirty-two types of stalagmites will have five factors affecting its growth. Some of these factors will have the upper limit and some of the factors will have the lower limit—it all depends upon the conditions surrounding the growth of the stalagmite. If these limits are substituted in the two foregoing formulas, a *relative* circumference and a *relative* rate of vertical growth can be calculated for each of the thirty-two types of stalagmites.

Also, by taking the two limits of the five factors as listed above, a "two-branching" or "dichoic" scale can be constructed, by means of which it is possible to tell the type that a given stalagmite belongs to, after first determining whether each of the five factors has the upper limit or the lower limit. This "dichoic" or "two-branching" scale now affords a way of finding out the type a stalagmite belongs to and, also, by means of the preceding method, to find out its *relative* circumference and its *relative* rate of vertical growth.

In Ingleborough Cave, Devonshire, England, there is a stalagmite called the "Jockey Cap," on account of its shape. This "Jockey Cap" stalagmite has been under observation since 1839, and its circumference growth and its rate of vertical growth are well known. By taking advantage of the measurements and comments of Dawkins[1] and Gordon,[2] the limits of the five factors governing the growth of the "Jockey Cap" can be ascertained, and accordingly the "Jockey Cap" can be classified by means of the "dichoic" scale as belonging to type 4. The mature circumference of the "Jockey Cap" may be estimated from the rate of circumference increase noted by Dawkins,[3] and using this mature circumference and the known rate of vertical growth of the "Jockey Cap," the *actual* circumference and the *actual* rate of vertical growth of type 4 becomes known. By the use of the *actual* circumference and *actual* rate of vertical growth of type 4 as a base, the *actual* circumference and *actual* rate of vertical growth for each of the thirty-two types can be obtained by means of the *relative* circumference and the *relative* rate of vertical growth previously calculated.

[1] *Op. cit.*, pp. 38–41, 442, and Appendix II.

[2] *Loc. cit.* [3] *Op. cit.*, pp. 40, 442, and Appendix II.

The probable shape of the face, the presence or absence of a "splash cup," the circumference, and the rate of vertical growth, for each of the thirty-two types of stalagmites, have been assembled in Table IV. In addition, the Dichoic Scale has been tabulated. It is now possible, after determining the limits of each of the five factors, to classify the stalagmite, by means of the Dichoic Scale, as belonging to a certain type, and then, as a check, to compare four of the characteristics of this type of stalagmite in Table IV.

DICHOIC SCALE

1. The drip is large.. See 3 or 4
2. The drip is small.. See 25
3. The air circulation is large.. See 5 or 6
4. The air circulation is small.. See 15 or 16
5. The humidity is high.. See 7 or 8
6. The humidity is low.. See 11
7. The temperature is high.. See 9
8. The temperature is low.. See 10
9. The concentration is high, type 1; it is low, type 2
10. The concentration is high, type 3; it is low, type 4
11. The temperature is high.. See 13
12. The temperature is low.. See 14
13. The concentration is high, type 5; it is low, type 6
14. The concentration is high, type 7; it is low, type 8
15. The humidity is high.. See 17 or 18
16. The humidity is low.. See 21 or 22
17. The temperature is high.. See 19
18. The temperature is low.. See 20
19. The concentration is high, type 9; it is low, type 10
20. The concentration is high, type 11; it is low, type 12
21. The temperature is high.. See 23
22. The temperature is low.. See 24
23. The concentration is high, type 13; it is low, type 14
24. The concentration is high, type 15; it is low, type 16
25. The air circulation is large.. See 27 or 28
26. The air circulation is small.. See 37 or 38
27. The humidity is high.. See 29 or 30
28. The humidity is low.. See 33 or 34
29. The temperature is high.. See 31
30. The temperature is low.. See 32
31. The concentration is high, type 17; it is low, type 18
32. The concentration is high, type 19; it is low, type 20

33. The temperature is high . . . . See 35
34. The temperature is low . . . . See 36
35. The concentration is high, type 21; it is low, type 22
36. The concentration is high, type 23; it is low, type 24
37. The humidity is high . . . . See 39 or 40
38. The humidity is low . . . . See 43 or 44
39. The temperature is high . . . . See 41
40. The temperature is low . . . . See 42
41. The concentration is high, type 25; it is low, type 26
42. The concentration is high, type 27; it is low, type 28
43. The temperature is high . . . . See 45
44. The temperature is low . . . . See 46
45. The concentration is high, type 29; it is low, type 30
46. The concentration is high, type 31; it is low, type 32

TABLE IV

TABLE OF CHARACTERISTICS

Type	Cup	Shape of Face	Rate of Growth	Circumference	Limits of Variable
			cm. per year	m.	
1	Shallow	Very convex	3000	0.6943	*D, A, H, T, C*
2	Deep	Very convex	300	0.6943	*D, A, H, T, c*
3	Shallow	Very convex	7.5	4.4	*D, A, H, t, C*
4	Shallow	Very convex	0.75	4.4	*D, A, H, t, c*
5	Deep	Very convex	15000	0.0981	*D, A, h, T, C*
6	Very deep	Very convex	1500	0.0981	*D, A, h, T, c*
7	Shallow	Very convex	450	0.6213	*D, A, h, t, C*
8	Deep	Very convex	45	0.6213	*D, A, h, t, c*
9	Shallow	Convex	0.2985	21.9120	*D, a, H, T, C*
10	Shallow	Convex	0.0299	21.9120	*D, a, H, T, c*
11	Very shallow	Convex	0.0075	138.9080	*D, a, H, t, C*
12	Shallow	Very blunt	0.0008	138.9080	*D, a, H, t, c*
13	Shallow	Very convex	15	3.1051	*D, a, h, T, C*
14	Very deep	Very convex	1.5	3.1051	*D, a, h, T, c*
15	Shallow	Very convex	0.3750	19.6416	*D, a, h, t, C*
16	Very deep	Very convex	0.0375	19.6416	*D, a, h, t, c*
17	Very shallow	Very convex	237.2250	0.0180	*d, A, H, T, C*
18	Shallow	Very convex	23.7225	0.0180	*d, A, H, T, c*
19	None	Very convex	5.7370	0.1131	*d, A, H, t, C*
20	Shallow	Convex	0.5737	0.1131	*d, A, H, t, c*
21	Very shallow	Very convex	11850	0.0026	*d, A, h, T, C*
22	Very deep	Very convex	1185	0.0026	*d, A, h, T, c*
23	Very shallow	Very convex	2933	0.0158	*d, A, h, t, C*
24	Very deep	Very convex	293.3	0.0158	*d, A, h, t, c*
25	None	Convex	0.2373	0.5667	*d, a, H, T, C*
26	Shallow	Blunt	0.0237	0.5667	*d, a, H, T, c*
27	None	Convex	0.0059	3.5816	*d, a, H, t, C*
28	Deep	Blunt	0.0006	3.5816	*d, a, H, t, c*
29	Very shallow	Very convex	11.8500	0.0805	*d, a, h, T, C*
30	Very deep	Convex	1.1850	0.0805	*d, a, h, T, c*
31	Shallow	Blunt	0.0293	0.5068	*d, a, h, t, C*
32	Shallow	Blunt	0.0029	0.5068	*d, a, h, t, c*

ACTUAL CLASSIFICATION OF STALAGMITES

If a stalagmite is extremely *unsymmetrical*, it may be necessary to classify it by sections. The classification, by circumference alone (a more or less uncertain procedure), will indicate its period of formation, but not how long ago it died. If a stalagmite is young (immature) and its drip large, its circumference will be less than that given in Table IV; if the stalagmite is young and its drip small, its circumference will be greater than that given in the Table IV.

More than one drop per second is a fast drip, over 2 feet per second (perceptible) is a large air circulation, over 50 per cent is a high relative humidity, over 68° F. is a high temperature, and over 50 per cent is a high concentration.

Count the drip, estimate the air, get the concentration by analysis (the absence of a healthy stalactite above indicates a high concentration if the cave has a pure limestone cover), and determine the temperature and humidity. If the stalagmite is in an open cavern or shelter, the yearly average temperature and relative humidity for the region may be taken.[1] A wet cave, of course, means a high humidity.

PRECAUTIONS NECESSARY

After determining your limits, classify by the Dichoic Scale and verify the measurements in Table IV. Always remember that the classification involves the extreme limits of the variables, and if unsatisfactory results are obtained re-examine the limits and, if any are doubtful, reclassify. Table IV is merely an approximation, and the figures are given to several decimal places to prevent a ragged appearance.

EXAMPLES OF CLASSIFICATION RESULTS

The actual figures are based on the Jockey Cap. Figure 16 shows an attempt to reconstruct this stalagmite from Dawkin's[2] measurements. On the basis of the foregoing calculations, this stalagmite now (1922) has a circumference of 3.53 meters, or 139 inches, at the points located by Dawkins.

[1] "Climatological Data by Sections," *U.S. Weather Bureau.*

[2] *Op. cit.*, pp. 40, 442, and Appendix II.

"The Pillar of the Constitution," Wyandotte Cave, Indiana,[1] classified by circumference alone (a precarious method), falls into type 10 as being the slowest-growing stalagmite consistent with its circumference. The age of this stalagmite has been estimated as follows:[2]

Authority	Rate of Growth	Period of Formation
	cm. per year	years
Collet	0.010	91,000
Collet	0.017	54,000
Collet	0.025	37,000
Hovey	0.025	37,000
Present estimate	0.030	30,500

The stalagmite in the Museum of Science and Art, Edinburgh[3] (classified again by circumference alone), required 560,000 years for its formation. Sir Alexander Milne measured the increase on the stump which accrued from 1819 to 1863 and estimated the age at 600,000 years.

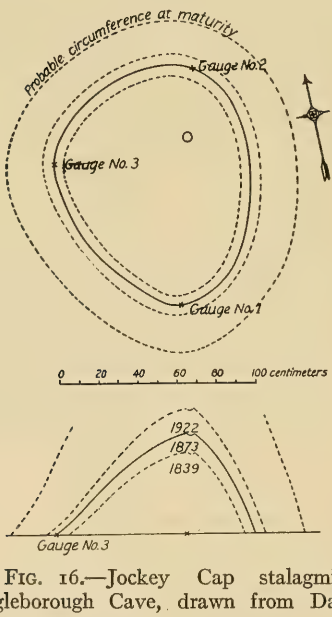

FIG. 16.—Jockey Cap stalagmite, Ingleborough Cave, drawn from Dawkin's measurements, 1873.

The Experimental Mine stalagmites fall in type 20, and agree fairly well in vertical growth (0.57 cm. against about 0.60 actual) and circumference. These stalagmites are undoubtedly calcite (W. M. Myers, petrographer, Pittsburgh Station, United States Bureau of Mines, reports that fragments of the stalagmites were uniaxial negative, refractive index from 1.486 to 1.658, and gave Meighen's reaction for calcite).

The change in shape, convexity of face, and circumference of the stalagmite from Robertson's Cave, near Springfield, Missouri,[4] were probably caused by a sudden increase in drip and an increase

[1] Farrington, *loc. cit.* [2] *Ibid.* [3] *Ibid.*, p. 255.

[4] Farrington, *op. cit.*, p. 1; vertical section, Plate 32.

in evaporation, accompanied by a slight movement of the drip.[1] This caused a more rapidly growing stalagmite of a little greater diameter.

Several stalactites and stalagmites are now under observation in Marengo Cave, Indiana,[2] but their growth is probably slow.

CONCLUSIONS

An approximation method for determining the age of stalagmites has been developed.

Symmetry in a stalagmite indicates constant growth conditions.

Stalagmites with circumferences of over 25 meters generally occur as stalagmitic or travertine layers, as they rarely have sufficient space to permit them to attain their mature circumference.

ACKNOWLEDGMENTS

I wish to thank Dr. Herbert Insley, formerly petrographer for the Pittsburgh Station of the United States Bureau of Mines, and now with the United States Bureau of Standards, at Washington, D.C., for his assistance and suggestions; also Dr. Clark Wissler, curator of anthropology, American Museum of Natural History, New York City, for his assistance in securing access to rather uncommon publications.

[1] *Ibid.*, p. 258.

[2] Farrington, *loc. cit.*

THE PHYSIOGRAPHIC DEVELOPMENT OF THE BIG THOMPSON RIVER VALLEY IN COLORADO[1]

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OUTLINE

INTRODUCTION

The Big Thompson River rises in a snow field within a large cirque on the east side of the Continental Divide in Colorado at about latitude 40° 20′ north. It flows in a general easterly direction down the slope of the Front Range to cross the foothills and the plains, joining the South Platte River east of Greeley. The portion of the Big Thompson River under consideration may be found on the Longs Peak, Mount Olympus, and Loveland quadrangles. The contour interval (100 feet) is too large, however, to permit map identification of many features included in this report. The accompanying sketch map (Fig. 6) gives the location of the various places discussed.

The composite origin of the Big Thompson Valley may be clearly shown from a study of the five distinct and successive physiographic units which make up its course from headwaters to foothills district. The separation of the different parts of the valley into five areas is based upon: (1) general outline and contour of the valley walls; (2) number and character of the tributary streams.

[1] Observations on the physiography of Big Thompson River Valley occupied parts of the field seasons of 1921 and 1922 while the author was engaged in a study of the Pre-Cambrian geology of the Front Range in northern Colorado.

DESCRIPTION AND CLASSIFICATION OF PHYSIOGRAPHIC UNITS

1. The first unit extends for about 12 miles from the Continental Divide east through Moraine Park (Fig. 6). Beginning at the Continental Divide the first unit is typical of the topography developed by late Pleistocene glaciation. At present the tributary in Spruce Canyon harbors the Sprague Glacier—a remnant of the larger masses of ice which grooved and scoured the granite and schist of stream-carved canyons into U-shaped valleys with many hanging tributaries. The chief tributary once occupied by the late Wisconsin ice is the Fall River, the lower part of whose valley was the melting basin (Horse Shoe Park) of an ice tongue similar to that which filled the Big Thompson in Moraine Park and developed huge lateral moraines.

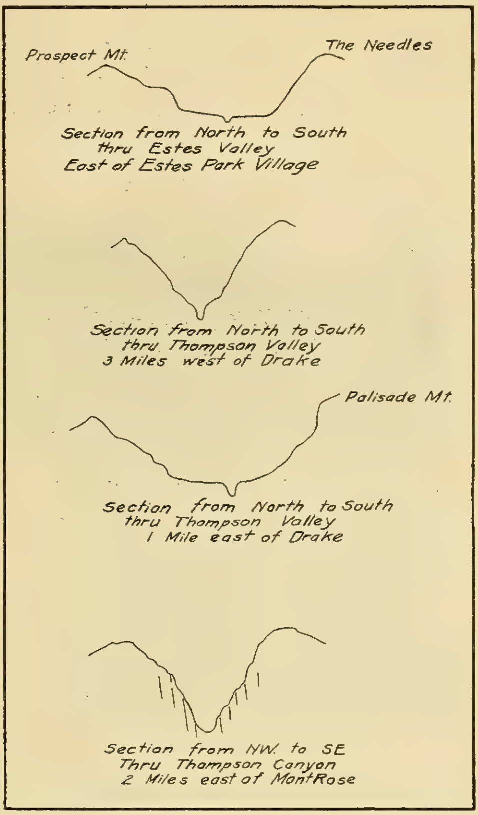

FIG. 1.—Diagrammatic cross-sections of the valleys of units 2, 3, 4, and 5 of the Big Thompson River Valley.

2. The second unit comprises the Estes Valley. This area has a broad, flat T-shaped outline. From Moraine Park to Estes Village the valley is from 1 to 2 miles wide. East of the Village it widens and lengthens north to Devils Gulch and south to include Fish Creek Valley. On all sides of this broad, flat surface granite walls rise abruptly so that for a distance of nearly 7 miles the valley is marked at its margin by precipitous granite cliffs, i.e., the Needles in Estes Park (Fig. 1).

Black Canyon on the north, Fish Creek Valley on the south, and Dunraven Valley on the east between Mounts Olympus and Pisgah are tributary to the Thompson within this area. They, like their main, are broad, open, and U-shaped. The Thompson has sunk its channel from 50 to 100 feet below the broad level of the Estes Valley and locally has developed intrenched meanders.

3. The third unit begins at the eastern end of the Estes Valley. The sides are sharply constricted within granite walls, making a V-shaped canyon with precipitous slopes increasing in steepness to the east of Loveland Heights and Glen Comfort. From Estes Valley to the Forks at Drake the river's course lies through a canyon whose tributaries are narrow gulches typical of youthful stream erosion.

Fig. 2.—View looking upstream through Mont Rose Valley (unit 4). Note the open U-shaped outlines of the valley walls with the sharp unglaciated peaks of Palisade Mountain in the distance.

4. The fourth unit lies between Drake and the east end of Mont Rose Valley (Fig. 2). In this area the Big Thompson Valley is wider than above Drake, although not as wide as in Estes, and has a broad, U-shaped outline. The stream has sunk its channel over 100 feet into the bottom of this open valley and has made a narrow canyon about 6 miles long which marks the last cycle of canyon cutting.

The North Fork enters the Thompson at Drake. This stream valley is open and U-shaped in outline with gently rounded *roche moutonné* surfaces developed on the granite in the upper part of the valley bottom. As seen from Bryant's Ranch the valleys of the North Fork and the Big Thompson are much alike. In fact they are so similar that one seems but a continuation of the other. The North Fork and the part of the Big Thompson between Drake and Mont Rose are in perfect harmony, while the upper part of the Big Thompson between Estes and Drake is entirely out of accordance with the lower reaches.

Cedar Creek, which enters the Thompson Valley about a mile west of Mont Rose, is also open and U-shaped, with steepened sides in accordance with the main valley. Small tributaries of the Thompson within the fourth unit are narrow gulches developed by recent stream erosion. All the gulches from Estes Valley to Mont Rose, however, were begun before the last cycle of canyon-cutting. When traced from their junction with the Thompson to their headwaters they show a narrow steep-walled canyon in the lower reaches opening out into wider middle and upper portions.

5. The fifth unit is the Loveland Canyon (Fig. 3). From Mont Rose to the foothills the valley is a deep box canyon whose sides rise from 100 to 1,000 feet above the stream. The lower walls are nearly vertical and are the dipping surfaces of almost perpendicular beds of highly indurated schist. For the most part the river's course lies along the strike of the schistosity and crosses the dip only at right angles with sharp and short turns.

FIG. 3.—Same location as Figure 2 but looking downstream into the gorge of unit 5.

The second and fourth units have the following features in common: (1) open flat-bottomed valleys with steep walls; (2) intrenched meanders in the bottom of the broad valleys. The third and fifth units also have many similar features as: (1) narrow, V-shaped outlines; (2) precipitous tributary gulches (Fig. 1). It will be shown that the second and fourth physiographic units have had a similar development, but entirely different in its aspects from the processes which developed units 3 and 5.

The course of the Big Thompson River lies almost at right angles to the strike of the Front Range and reveals a section of the Pre-Cambrian beds from the Continental Divide to the foothills.

The river's course is a series of sharply twisted meanders. Where straight stretches do occur they lie along dipping beds of schist and the more abrupt turns follow the prevailing joint systems in the granite and schist. The river first crosses granite with small amounts of schist, then crosses an area chiefly of granite from Estes Valley to Loveland Heights. To the east the granite is more and more interrupted by schist until at Drake, schist and massive pegmatite dikes predominate. East of Drake, through the fourth and fifth units, the course is parallel to the dip of the steeply dipping beds of schist for most of the distance. Both units, although so different in appearance, are developed in much the same sort of rock. The schist, except locally, is the least resistant, the pegmatite next, and the granite the most resistant of the rocks exposed along the river's course. Hence canyons in schist at the lower end of the valley and broad, open stretches in granite near the upper part must owe their sequence to factors other than simple stream erosion.

PRE-WISCONSIN GLACIATION

It is believed that there are, within the area drained by the Big Thompson, evidences of a much earlier Pleistocene glaciation than the late Wisconsin invasion. There are four principal lines of evidence of this earlier glaciation.

1. *U-shaped valleys.*—The U-shaped outlines of portions of the main valley have already been pointed out in the description of the second and fourth units. Mountain valleys which have been occupied by glaciers always show a characteristically U-shaped profile, rounded and scoured by the ice to its upper limits on the valley walls, with the surrounding unglaciated peaks left steep and serrate. The profile of Mont Rose Valley (Figs. 1 and 2) shows a typical U-shape, with Palisade Mountain exhibiting steep and sharp peaks above the rounded outline. The Estes Valley is also distinctly U-shaped, but the ice evidently rose to overlap its margin north and south of Estes Village. To the east, however, the profile of Mounts Olympus and Pisgah exhibit sharp peaks which stood well above the ice in the valleys below.

In addition to these regions already described there are flat areas of oval shape such as the Orchard and Cedar Park (Fig. 4).

They have the appearance of having been the melting basins of ice which gathered from the surrounding highlands. The appearance of peaty beds in the soil of Cedar Park adds to this evidence although no true till has yet been recognized from the area.

2. *Remnants of early till.*—There are remnants of early till exposed along the roadside at the east end of Mont Rose Valley. This till is made up of granite bowlders, with rounded and scored surfaces, buried in a matrix of bluish clay. The whole is overlain by stratified beds of sand and clay topped by coarse gravels.

Fig. 4.—Cedar Park—probably the melting basin of glaciers which centered around Storm Peak in the distance.

Small patches of glacial bowlders and terrace gravels lie about 50 feet above the river on a rock terrace at Cedar Cove. They are probably remnants of more extensive glacial deposits belonging to the earlier ice invasion. River erosion since ice occupation has re-worked these deposits—carried off most of the lighter sands and rock flour, leaving only the larger bowlders perched above the present course of the river, which has intrenched itself in recent times from 50 to 100 feet below the old glaciated floor. Recent talus and slumpings may have covered most of the drift remnants which might be expected to remain along the sides of the valley east of Drake. In the Estes Valley, no true till remnants remain, but terrace gravels of water-worn glaciated pebbles perch about 100

feet above the stream level at the base of steep granite walls on the north side of the valley.

3. *Potholes.*—Nearly every exposure of granite in the Estes Valley is marked by several well-defined potholes which vary in size from some 3 or 4 inches in diameter and 1 or 2 inches deep to others 2 feet deep and 4 feet across (Fig. 5).

Most of them are nearly circular with the margin broken down on one side. The margins of these potholes have been etched by weathering so that large angular feldspar crystals protrude into

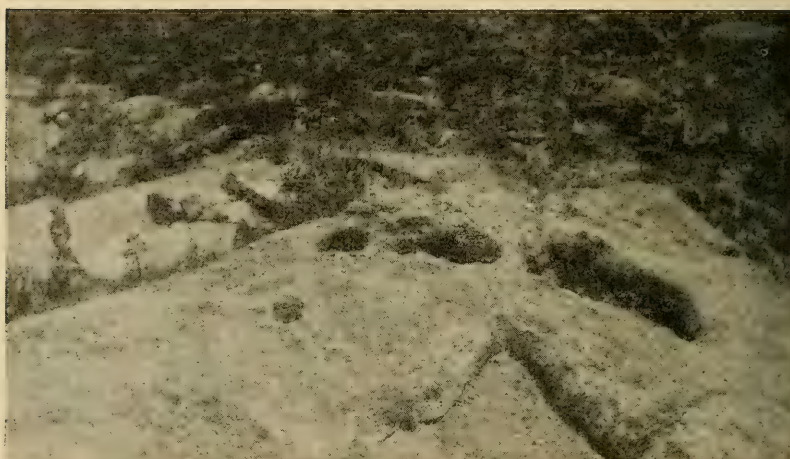

FIG. 5.—Glacial potholes cut in granite along the Estes Valley

the cavity like small teeth. Within the holes the surface is smoother, and in some grooved so deeply that a secondary pothole has been cut within the original one.

These potholes are found at all elevations from the summit of Prospect Mountain, 8,896 feet, and the Needles, 10,075 feet, to the level of 7,500 feet on the floor of Estes Valley. They also appear in Fish Creek Valley up to the top of Lily Mountain, 9,793 feet. They are believed to mark the margin of early glaciers which filled the Estes Valley where whirlpools following the drainage retreated into the valley with the floods from the waning ice. From Drake to Mont Rose there are a few poorly preserved potholes in the schist. It appears that the schist and pegmatite are not massive enough to

preserve the form of those that might have existed and probably were too fissile to allow the production of potholes on the scale to which they appear to have been developed in the granite.

4. *Interrupted and reorganized drainage lines.*—The interrupted and reorganized drainage lines are directly the result of the ice occupation of units 2 and 4.

The diagrams in figures 6 and 7 suggest a possible analysis of the drainage before and after the early glaciation. The valley of

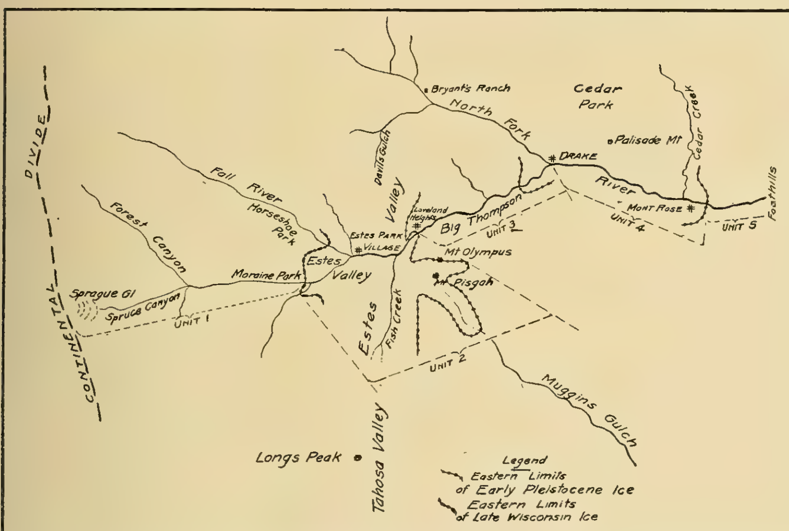

FIG. 6.—Diagram of the present drainage of the area showing influence of early and late glaciation on the present drainage lines.

Muggins Gulch is suggested as the outlet of the upper Thompson in preglacial times. The North Fork is shown as the headwaters to the lower part of the Thompson of today. Small tributaries to each occupied the present course of the Big Thompson between Estes Valley and Drake and were separated by a low col.

The early ice gathered on the highlands to the west and moved down the Estes Valley as far east as Mount Olympus, while small valley glaciers filled in Black Canyon and the valleys around Olympus and Pisgah. Probably Park Hill and Muggins Gulch were also full of ice, and possibly all of the Estes Valley south to include

Tahosa Valley. The Estes Valley was the melting basin of this whole system of glaciers, though the drift deposits left in the glaciated area have been cleared out by long and active erosion of the stream and ice tributaries, leaving a U-shaped valley as chief evidence of its occupancy. Simultaneously ice gathered in the valleys adjacent to Storm Peak and filled in the North Fork, Cedar Park, and the Thompson Valley between Drake and Mont Rose.

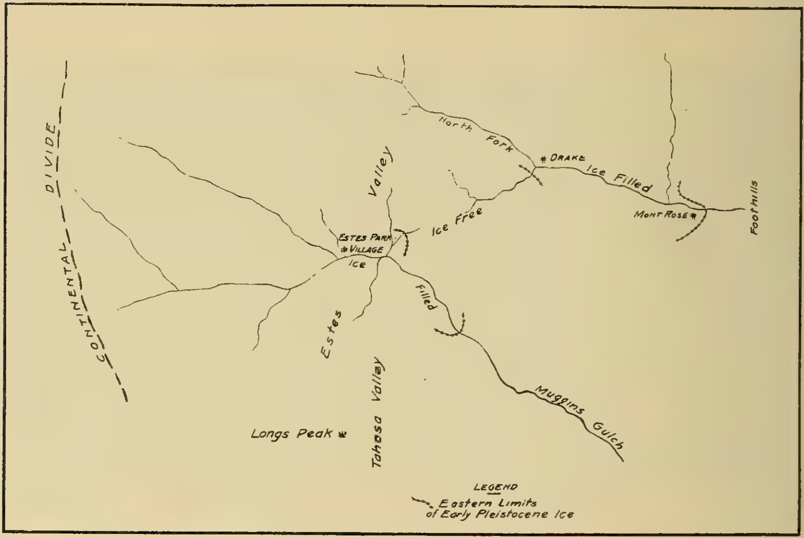

FIG. 7.—Diagram to represent the suggested drainage systems which preceded early Pleistocene glaciation of this area.

When the Muggins Gulch outlet was filled with ice to the 9,000-foot level, drainage traveled from Estes to Drake over the low col and through the small tributaries. This outlet became more important as an escape for all the waters from the upper Thompson after the ice had melted from the lower altitudes of the Thompson Valley east of Drake. On account of its lower elevation the ice freed the area east of Drake while it may have lingered for some time in the Estes Valley to the west. As a result, the drainage once established along its present lines east of Estes rapidly cut down its course below the 8,000-foot level, thus determining the upper canyon

of the Thompson. When the ice finally melted from the Estes basin to the west, drainage had been permanently established along its present lines throughout most of the Thompson Valley.

The combined features of U-shaped valleys, remnants of till, glacial potholes, and interrupted and reorganized drainage furnish ample proof that glaciers invaded, eroded, and melted from portions of the Thompson Valley in early Pleistocene times.

HISTORY OF THE UNITS IN THE BIG THOMPSON VALLEY

The five different units comprising the Thompson River Valley are believed to have been the result of several processes affecting two distinct river systems.

The essential elements of these processes in chronological order comprise: (1) normal stream erosion; (2) Early Pleistocene valley glaciers; (3) Early glacial drainage; (4) late Pleistocene valley glaciers.

Normal stream erosion first determined the courses of both river systems. Probably both streams developed steep-walled canyons along much of their courses. The areas occupied by units 1 and 2 of the present Thompson River Valley were the upper reaches of the western (Muggins Gulch) river system, while units 2 and 4 comprised the middle portions of the eastern (North Fork) river valley. Unit 3 is the connecting link between these areas and is the youngest topographic feature of the present Thompson Valley. Unit 5, which was the lower part of the eastern river valley, is probably the only unmodified portion of these early systems which were incorporated into the Thompson. As far as the present analysis goes, this gorge (unit 5) has been a simple stream-carved canyon throughout its history.

The stream cycle of erosion was interrupted by early Pleistocene valley glaciers which filled in the headwaters and middle reaches of both river systems modifying the outlines of the parts which later became units 1, 2, and 4 from V-shaped gorges to open U-shaped valleys. Drainage from the western ice-filled valley escaped both through Muggins Gulch and over the low col to the east through the eastern stream valley to the foothills. The later outlet became the site of *all* the drainage from the west when the

waters had cut the new eastern outlet below the level of Muggins Gulch after the ice had left the eastern (North Fork) valley.

Proofs of the exceedingly youthful character of unit 3 are derived from a study of the gradient of the present Thompson Valley.

The gradient of the Big Thompson River averages from Estes to the foothills about 100 feet per mile. About 3 miles west of Drake along unit 3 the gradient is nearly 250 feet per mile for a distance of over 2 miles. This is the steepest fall along the river's course which is here between nearly vertical canyon walls cut alike in granite and schist. As far as erosion by the stream alone is concerned this stretch is the youngest topographic feature along the entire course of the river. This portion of the valley is solely the result of stream erosion established by early glacial drainage across a low divide which developed into a steep and winding canyon widening east to Drake and west to Estes Valley.

The early Pleistocene glaciers left units 2 and 4 much as they are today except that recent stream erosion resulting from an upwarp of at least 100 feet over much of the area has cut a canyon 50 feet to 100 feet deep in the floors of units 2 and 4 and has cleaned out the early glacial débris from the botton of the valley.

In late Pleistocene (probably late Wisconsin) times ice again advanced over part of the course of the Big Thompson but to a much less extent than in early Pleistocene times. The limits of this invasion mark the boundaries of unit 1 where massive terminal moraines separate the areas which have been influenced by both early and late glaciation (unit 1) from that which was covered by the early ice only (unit 2).

During and perhaps previous to late Wisconsin glaciation the Big Thompson Valley stood about 100 feet lower than at present. At any rate, débris from the melting of the ice was deposited as a thick layer of sand and gravel over the flatter parts of the valley floor outside of the late Wisconsin ice area.

As the Wisconsin ice vanished an upwarp of at least 100 feet affected most of the area. The river promptly dissected most of the terrace deposits and began sinking its channel into the bedrock, producing a canyon within a canyon in units 3 and 5 and letting a narrow canyon nearly 100 feet deep into the broad floors of units 2

and 4. At the present time these inner canyons are being rapidly degraded, and at no points outside of unit 1 is there any aggradation taking place.

SUMMARY

The composite course of the Big Thompson River Valley comprises five units linked together as a result of the complex physiographic history of the area from the Continental Divide to the foothills district.

Lines of evidence point to two distinct river systems flowing independently but in the same general direction to the foothills. Canyon-cutting by these two streams was interrupted by early Pleistocene glaciers which filled in the headwaters and crept far down each valley toward the foothills. The glaciers blocked the normal drainage outlets of the western (Muggins Gulch) river system and its waters traveled east over a low divide to the eastern (North Fork) valley which, because of its lower altitude was freed from ice while glaciers still filled the western area. The drainage lines thus established from the western to the eastern river systems became the connecting link in the new river valley—the Big Thompson of today. Late Pleistocene glaciers affected only the headwaters of this new system and are in no way responsible for the general course of the Big Thompson.

Thus the present river valley is made up of the glaciated headwaters of one river system joined by a young precipitous stream-carved canyon to the glaciated middle portions of another river system and the whole extends east through a river-cut gorge across the foothills and the plains of eastern Colorado to join the North Platte River east of Greeley.

NOTES ON MUD CRACK AND RIPPLE MARK IN RECENT CALCAREOUS SEDIMENTS[1]

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During a trip to Florida and the Bahamas in the winter of 1920, the writer kept in view as one of the objects of his seashore studies the discovery of localities favorable for noting the characteristics of mud cracks in Recent sediments. It seemed desirable that the results obtained in laboratory experiments dealing with this subject should be checked by comparison with mud cracks formed on the seashore. The following notes include also some observations relating to ripple marks on calcareous sand.

MUD CRACKS

In the writer's experimental work, saline and non-saline mud cracks were shown to develop, under the experimental conditions imposed, sharply contrasted features. The polygons of the non-saline mud cracks turned upward while those of the saline mud cracks remained flat or curved slightly downward. It was stated in this paper[2] that while the experiments indicated the tendency of the polygon margins to curl upward in the one case and remain flat or curve downward in the other, the conditions found in nature may often disguise or prevent any effective exhibition of these contrasting tendencies. It was pointed out also that "the marked differences observed in the experiments between the behavior of fresh-water, highly saline, and moderately saline muds are not ordinarily so well marked in nature as the accompanying illustrations might lead the reader to expect."[3]

In the following notes the reader will see to what extent the conclusions reached from experimental work regarding the contrasts

[1] Published with the permission of the director of the Geological Survey of Canada.

[2] "Some Factors Affecting the Development of Mud Cracks," *Jour. Geol.*, Vol. XXV (1917), pp. 135–44.

[3] *Op. cit.*, p. 143.

between saline and non-saline mud cracks are supported by seashore observations made in Florida.

In southern Florida, the calcareous deposits commonly met with on or near the beach consist either of calcareous sand or flocculent calcareous ooze. The two kinds of deposits are apt to be sorted by wave and current action both on the beach and in the shallow waters near shore in much the same manner as ordinary mud and quartz sand, resulting in beaches of pure white or cream-colored sand separated by bays of soft gray ooze containing more or less intermixed calcareous sand. The calcareous sand suffers no appreciable loss of bulk on drying and consequently does not sun-crack. Since this material forms the bathing beaches which are familiar to tourists from the North, the casual visitor is apt to get the impression that mud cracks do not develop on the recently formed calcareous marine deposits. The soft, flocculent, calcareous mud, however, reacts to sun and atmospheric exposure in the same way as ordinary mud. The writer was able to see examples of mud cracks on the calcareous mud at only a few localities. One of these is the shore line on Key West Island between the bathing-beach and the United States Bureau of Fisheries laboratory. The flat limestone shore here lies but slightly above the high tide line. At a few points along this shore a thin veneer of calcareous mud occurs both within the intertidal zone and slightly above it, where it has been left during spring tides or periods of unusual inundations accompanying storms. Along this stretch of shore good examples of mud cracks were seen both in the salt-water zone and above it. In the latter, all the examples observed showed polygons with the margins turning up. In the salt-water mud cracks the margins curved downward often sufficiently to lift the center of the polygon clear of the ground.

Various other stretches of the shore line, both in south Florida and on Providence Island, Bahamas, were examined for mud cracks, but no very satisfactory localities were seen for extensive subaerial exposures on natural beaches of the type of calcareous sediment capable of developing mud cracks. Fortunately, however, the extensive dredging operations, which were undertaken for the purpose of reclaiming swamp land near Miami beach, gave the

writer an opportunity to see several acres of the calcareous mud which forms much of the bottom of the northern part of Biscayne Bay exposed to subaerial conditions. North of the causeway to Miami beach six or eight acres had been covered by gray calcareous mud pumped from the shallow sea bottom by hydraulic dredges. The resulting expanse of mud cracks furnished an exceptional opportunity for observing the kind of mud cracks which this type of sediment will yield (Fig. 1).

These mud cracks show a considerable range in the size of the polygons. Over most of the area the polygons were from 6 to 15

FIG. 1.—Mud cracks in calcareous mud, Miami, Florida. Note terrace-like margins of polygons.

inches in diameter, with cracks separating them which were mostly from $2\frac{1}{2}$ to 3 inches wide, but with a minimum and maximum range of from $\frac{3}{4}$ to 4 inches in width. The depth of the cracks generally ranged between 8 and 15 inches. One part of the area was noted where the polygons ranged between 1 and $3\frac{1}{2}$ feet in diameter with the separating cracks averaging 3 inches in width (Fig. 2). These large polygons showed none of the tendency to split up into laminae seen in some of the smaller ones (Fig. 3). The margins of the polygons of Figure 1 show clearly three or four laminae exposed, the unequal rates of shrinkage having developed terrace-like margins along the fissures. The different-sized polygons noted in different parts of the Miami mud cracks probably correspond to differences in the desiccating power of the sun when they were formed. A high

temperature tends to produce more widely spaced mud cracks than a lower one, according to the writer's experiments.[1]

With reference to curvature or flatness of the surfaces of the polygons, the behavior was nearly but not entirely uniform. With a very few exceptions, the polygons showed flat or very nearly flat

FIG. 2.—Mud cracks with flat-topped polygons 1′ to 3½′ in diameter; Miami, Florida

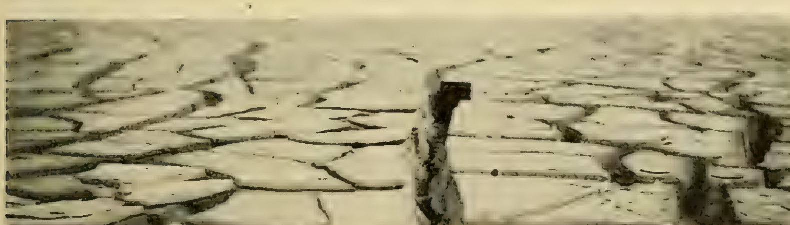

FIG. 3.—Calcareous mud cracks splitting into laminae; Miami, Florida

surfaces (Figs. 1–3). In the case of an area of small polygons, a few examples of polygons with upturned margins were noted (Fig. 4). In some instances the reverse curvature was noted, the margins of the polygons curving down ½ inch or a little more.

The observations made at Miami and Key West appear to indicate that absolute uniformity does not prevail in the behavior of saline mud cracks with reference to curling. In the great

[1] *Op. cit.*, p. 143.

majority of cases, however, the surface layers of the polygons either remain flat or warp down at the margins. The downcurling appears to be general only when the thickness of the mud is very slight as in the cases observed at Key West.

RIPPLE MARKS

With few exceptions the published observations on ripple marks of recent deposits relate to quartz sand ripple marks. In subtropical

FIG. 4.—Calcareous mud cracks with small polygons showing in some cases polygons with margins slightly upcurved; Miami, Florida.

and equatorial latitudes, calcareous sand frequently entirely supplants quartz sand on the beaches and in near shore waters. The specific gravity of the two kinds of sand is essentially the same and they react to wave and current action in much the same way.

It may be profitable to describe briefly the conditions under which ripple marks are now being impressed on calcareous sediments or potential limestones at certain localities in the Florida-Bahama region easily accessible from main routes of travel.

The waters adjacent to Providence Island in the Bahamas afford good opportunities to see ripple marks on calcareous sand at certain localities near the city of Nassau. The channel between

Hog Island and Providence Island, which generally has a depth of from 1 to 3 fathoms, furnishes conditions favorable to the development of tidal currents of varying velocities between Nassau and the reefs of living corals 4 miles east. The currents are strong enough near the corals to keep the limestone bottom to which they are attached swept clean of calcareous sand.

Between the reefs and the east end of Hog Island, considerable stretches of the bottom are covered with white sand on which numerous patches of "sea grass" are growing, which partially or entirely prevents the development of ripple marks. Farther west where the "grass" is absent the white sand, consisting largely of coarse, shell fragments, is marked by ripple marks with short wavelength (2 to 4 inches) of the ordinary current-mark pattern (see photograph by Kindle).[1] Over the easterly part of the white sand bottom, where the currents probably have their maximum strength, the bottom is covered with sand waves or metaripples.[2] These have a wave-length estimated at from 15 to 20 feet and an amplitude of 6 to 8 inches.

The waters of Biscayne Bay, Florida, furnish a considerable area of white calcareous sand bottom under water sufficiently shallow (12 to 18 feet) to permit careful inspection from a glass-bottomed boat. Much of the bottom between Miami and Cape Florida is covered with marine plants which prevent the occurrence of ripple marks. Near the Cape, however, waves and currents have kept the bottom free from plant colonies. Asymmetric ripple marks with rather long wave-length were observed near Cape Florida. A short distance from the steamer landing on the west side of the Cape parallel ridges of the sand wave type were seen spaced 25 to 50 feet apart. In the deeper water highly irregular bottom features occurred somewhat comparable in complexity of pattern with the flat-topped sand ridges at Annisquam, Massachusetts, illustrated by Kindle.[3]

[1] E. M. Kindle, "Recent and Fossil Ripple Mark," *Can. Geol. Surv., Mus. Bull.* 25 (1917), Plate VII.

[2] W. H. Bucher, "On Ripples and Related Sedimentary Surface Forms and Their Paleogeographic Interpretation, Parts I and II," *Amer. Jour. Sci.*, Vol. XLVII (March–April, 1919), p. 181.

[3] *Op. cit.*

So far as can be judged from the literature, fossil limestone ripple marks generally show a wave-length of from 1 to 5 feet. The widely spaced ripples with a wave-length of 15 feet or more, which appear to be very common on the calcareous sand of the Bahama-Florida regions, do not seem to have been noted in limestones. Ripples with a wave-length of only 2 or 3 inches appear likewise to have generally escaped the notice of geologists. This apparent discrepancy between the size of the ripple marks of limestone and that of calcareous sea bottom will probably disappear when search for such features becomes more thorough.

Ripple marks of unmistakable current-ripple type with a wave-length of $1\frac{1}{4}$ inches and amplitude of $\frac{1}{8}$ inch are represented in the Canadian Geological Survey collection by a specimen from the Upper Devonian limestone of the Hay River section, North West Territory, collected by Mr. E. J. Whittaker. No other example of ripple marks of equally or comparably small wave-length in limestone has come under the notice of the author although symmetrical ripple marks of similar wave-length and amplitude in sandstone are very common.

Miller[1] states that small ripple marks with a wave-length of from 1 to 2 inches and amplitude of $\frac{1}{2}$ inch occur at several horizons in the Pamelia, Lowville, and Trenton, but does not indicate whether they are current or oscillation ripples.

The numerous examples of Palaeozoic limestone ripple marks described by Prosser include both symmetrical and asymmetrical ripples but all are forms with long wave-length, generally from 20 to 36 inches. In several cases they are described as "clearly asymmetrical,"[2] or with slopes steeper to the west than to the east. thus leaving no question as to their current origin. In other cases Prosser found "no difference in the slope." Udden[3] notes limestone ripples which are "slightly unsymmetrical."

[1] William J. Miller, "Geology of the Port Leyden Quadrangle, Lewis County, N.Y.," *Bull. N.Y. State Mus., No. 135* (1910), p. 36.

[2] Charles S. Prosser, "Ripple Marks in Ohio Limestones," *Jour. Geol.*, Vol. XXIV, No. 5 (July–August, 1916), p. 459.

[3] J. A. Udden, "Notes on Ripple Marks," *ibid.*, No. 2 (February–March, 1916), p. 125.

Bucher[1] has brought together measurements of a number of limestone ripples with large wave-lengths which are "nearly symmetrical," and has raised the question whether the formation of such large ripple marks by wave action is possible.[2] He writes, "Since a neutral name is desired for the large, nearly or completely symmetrical ripples showing no assortment of grain, I suggest the term 'pararipples.'"[3]

The writer considers the pararipples to represent metaripples sufficiently modified either by wave action or reversed tidal currents to have lost their original asymmetry.

The association of mud cracks with limestone ripple marks having a wave-length of 2 feet in the Ordovician of southeastern Indiana, reported by Shannon,[4] would be significant in this connection if it should be found that they are symmetrical. Ripple marks 2 feet from crest to crest certainly could not have been formed by wave action in water shallow enough to permit the formation of mud cracks at low tide.

Limestone ripple marks of large amplitude have sometimes been inferred to represent water of considerable depth.[5] The writer's observations on the large ripples, now being formed in the shallow waters of the Bahamas, on calcareous sediments have convinced him that no trustworthy conclusion regarding the depth can be drawn unless the ripples can be shown to be of the oscillation type. The widely spaced ripple marks frequently met with in limestones have probably been in nearly all cases formed by currents. Since the wave-length and amplitude of current ripples depends chiefly upon the velocity of the current, and not at all upon depth, no reliable deductions regarding the latter can be drawn from them.

[1] *Op. cit.*, p. 260.

[2] *Ibid.*, p. 262.

[3] *Ibid.*, p. 263.

[4] "Wave-Marks on Cincinnati Limestone," *Proc. Ind. Acad. Sci.* (1894–95), pp. 53–54.

[5] J. Locke, "Professor Locke's Geological Report," *Ohio Geol. Surv., Second Ann. Rept.* (1838), p. 247, Plate 6.

ALGAE, BELIEVED TO BE ARCHEAN

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During recent years attention has been called to the widespread occurrence of fossils in Huronian rocks.[2] These fossils are mainly algae, although bacteria,[3] including iron bacteria,[4] have been found. The work on the origin of the iron-bearing formations of northeastern Minnesota led the writer to a close examination, not only of the Huronian cherts, but also of the Archean Soudan formation and the overlying conglomerates.[5] The discovery of micro-organisms in chert pebbles at the base of the Pokegama quartzite (Upper Huronian) of the Mesabi range[6] encouraged the search for organisms in still older conglomerates. This resulted in the finding of fossil algae in pebbles of the Ogishke conglomerate.

The Ogishke conglomerate is the lowest formation of Huronian age north of Lake Superior, and overlies directly the Archean basement complex. It is highly folded and metamorphosed. The pebbles in it include all the varieties of rocks found in the Archean

[1] Published by permission of Dr. W. H. Emmons, director, Minnesota Geological Survey.

[2] C. D. Walcott, "Pre-Cambrian Algonkian Algal Flora," *Smiths. Inst. Misc. Coll.*, Vol. LXIV, No. 2, 1914; *ibid.*, "Notes on Fossils from Limestone of Steeprock Lake, Ontario," *Geol. Surv. Canada, Mem. 28,* 1912, p. 16; E. S. Moore, "The Iron Formation on Belcher Islands, Hudson Bay, etc.," *Jour. Geol.*, Vol. XXIV (1918), pp. 412–38; Grout and Broderick, "Organic Structures in the Biwabik Iron-bearing Formation of the Huronian in Minnesota," *Amer. Jour. Sci.*, Vol. XLVIII (1919), p. 199.

[3] C. D. Walcott, "Discovery of Algonkian Bacteria," *Proc. Nat. Acad. Sci.*, Vol. I, (1915), p. 256.

[4] J. W. Gruner, "The Origin of Sedimentary Iron Formations: The Biwabik Formation of the Mesabi Range," *Econ. Geol.*, Vol. XVII (1922), p. 418.

[5] N. H. Winchell, "Geology of Minnesota," *Geol. Nat. Hist. Surv.*, Vol. IV (1899), p. 282; J. M. Clements, "The Vermilion Iron-bearing District of Minnesota," *U.S. Geol. Surv., Mon. 45,* 1903, p. 274; C. R. Van Hise and C. K. Leith, "The Geology of the Lake Superior Region," *U.S. Geol. Surv., Mon. 52,* 1911, p. 129.

[6] J. W. Gruner, *op. cit.*, p. 420.

beneath it. In some places greenstone pebbles predominate; in others, granitic ones, while in some areas chert pebbles, associated with red jasper pebbles, are abundant. Most of them are subangular though well worn, and as a rule they do not exceed 2 inches in diameter. Their chert and jasper cannot be distinguished from that of the Soudan formation. Even the finely banded structure so common in the Soudan formation is frequently found in the pebbles. There seems, however, to be a slight difference in the size of the grain of the Soudan chert found in place and that found in the pebbles. It is the opinion of the writer that the pressure on the chert pebbles was diverted to some extent by the yielding of the more or less heterogeneous and possibly still porous matrix around them. The chert pebbles, being the hardest and simplest in chemical composition, emerged from metamorphism without apparent change, while greenstone pebbles were elongated in many instances. This reasoning led to the original microscopic examination of pebbles.

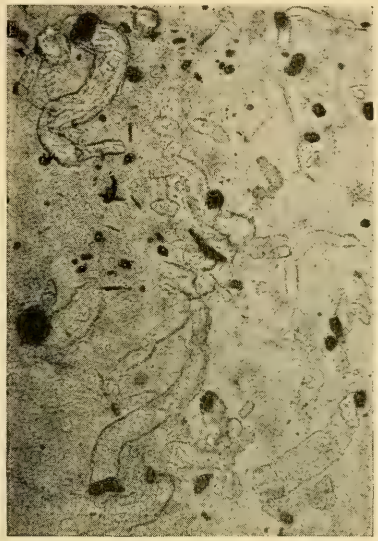

FIG. 1.—Blue-green algae. (Slide M 1053 D.) *Inactis* or *Microcoleus.* ×190.

FIG. 2.—Tracing of alga with canal. The same slide as in Figure 1. ×400.

The pebbles examined were dug with difficulty out of apparently glaciated rock surfaces on a number of islands in Ogishke Muncie Lake. Some were collected from the outcrops on the north shore of the lake. The two pebbles which contain the algae (Figs. 1, 2, and 3) come from an island in the S.W. $\frac{1}{4}$, Sec. 23, T. 65 N., R. 6 W. The pebbles are gray in color. The fossils consist of carbonate, the exact nature of which cannot be determined without risking the slides. The

matrix of the organisms is a very fine-grained chert containing many minute needles of brownish amphibole, very small crystals of carbonate of the same kind as that of the fossils, some magnetite, and minute specks of pyrite. This is exactly the composition of the chert of the Soudan formation in place. The latter, however, is slightly more recrystallized.

For the identification of the fossils the writer is indebted to Professor Josephine Tilden, algologist at the University of Minnesota. Professor Tilden classes them as blue-green algae corresponding to such types as *Inactis* or *Microcoleus*. Some of the structures which represent the sheaths of the plants show the "canals" in which the algae proper lived. Figure 2 is a tracing (taken from a photograph) of such a sheath, showing the "canal."

FIG. 3.—Blue-green algae. (Slide M 931 B.) ×2,200.

Since the publication of the paper on the origin of the Biwabik iron-bearing formation,[1] more algae of Huronian age have been discovered in chert of the same kind and from the same locality as that which contains the iron bacteria. The algae consist of chert, or are replaced by some brownish or greenish iron-containing mineral. Figure 3 is a highly magnified (×2,200) view of one of these organisms which, according to Professor Tilden, also belong to the blue-green algae of the type *Inactis* or *Microcoleus*. They are so small and inconspicuous at a magnification of less than 100 diameters that they escape attention. It is not improbable, therefore, that examination of rocks with this purpose in view will reveal fossils previously overlooked on account of their extremely small size.

In conclusion, the author expresses the belief that the blue-green algae in the chert pebbles of the Ogishke conglomerate are of Archean age, and that algae and bacteria were partly responsible for the deposition of the Soudan formation.

[1] J. W. Gruner, *op. cit.*

AN ASSOCIATION OF KAOLINITE WITH MIAROLITIC STRUCTURE[1]

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While engaged in geologic mapping of the Wrangell district in southeastern Alaska, the writer collected a suite of specimens which seem to illustrate very well one mode of origin of kaolinite, though not the most common one.

The general geology of the occurrence is as follows: A long, narrow stock of granite—possibly 25 miles long and 2 miles wide—extends across Etolin Island in a southeast-northwest direction, and is intrusive into a much larger stock of diorite. On the southeast side of Zarembo Island, farther to the northwest, along the same general line of strike, small stocks and intrusive masses of granite porphyry and rhyolite porphyry are found in slates, and are presumably outlying masses of the main stock. Many small masses of conspicuously miarolitic granite porphyry, intrusive into schists, are also found on the islands of Ernest Sound to the northeast of the main stock. The kaolinite in question occurs as fillings in druses in the rhyolite porphyry, and as an alteration product of the plagioclase feldspars in the granite porphyry of the Etolin Island stock. The rocks examined are in a glaciated region and are fresh and unweathered.

At the southeastern end of the granite stock the rock is a medium-grained pink granite, with a compact granitoid structure. The major component minerals are microcline-microperthite and quartz, with about 10 per cent or more of albite-oligoclase, a little hornblende and biotite, and accessory zircons and magnetite. About 12 miles northwest, the rock has changed to a pink granite porphyry with granophyric ground-mass and a prominent miarolitic structure. The druses average about one-half centimeter in diameter, and are

[1] Published by permission of the Director, United States Geological Survey.

lined with terminated quartz crystals and well-bounded crystals of microperthite projecting into the cavity. In the miarolitic cavities of the granite porphyry masses of Ernest Sound, hexagonal biotite crystals are common in addition to the quartz and feldspar. About 12 miles farther to the northwest, on Zarembo Island, are the small masses of white rhyolite porphyry intrusive into slates. The rhyolite porphyry is exceptionally miarolitic, and the volume of the druses, as measured on the polished surface of a hand specimen, is about $4\frac{1}{2}$ per cent. The druses vary from the fraction of a centimeter to a centimeter in diameter. These druses are lined with terminated quartz crystals projecting into the cavity, and are associated or flecked with many small plates of crystalline hematite (specularite). The druses are further partially or completely filled with a microcrystalline granular aggregate of kaolinite (Av. $n = 1.564 \pm .003$), and the central portion is usually filled with calcite. In some specimens kaolinite is absent and calcite alone fills the central portion.

If we consider the texture of the different facies of the rock to indicate the physical conditions during consolidation, an interesting correlation may be made between these conditions and the miarolitic structure and mineral association of the druses. The medium-grained granite with only a faint trace of porphyritic texture is compact, and presumably cooled so slowly that opportunity was given for the mineralizers in solution to escape gradually. The granite porphyry may be considered to have suffered an abrupt change in its rate of cooling, probably accompanied by increased viscosity, so that either the released gases or residual fluid were in part temporarily trapped, and deposited the pneumatolytic minerals in the druses. The mineral association of the druses—quartz, microperthite, and biotite—is characteristic of high temperature and pressure. The rhyolite porphyry represents a still more abrupt change in rate of cooling and a lower drop in temperature. The abrupt crystallization attendant upon this may have resulted in an increased vapor pressure, resulting in larger and more prominent druses than in the granite porphyry. The mineral association of the druses—quartz and specularite—is one such as is found in the early stages of the formation of zeolites in surface flows.

The kaolinite and calcite were deposited in the druses of the rhyolite porphyry still later than the quartz-specularite combination, and hence probably at still lower temperatures under hydrothermal conditions. The possible source and origin of the kaolinite is indicated by certain phenomena found in the granite porphyry now exposed at the surface. The plagioclase feldspars of this rock are zoned, and the more basic cores of many of them have been altered to fibrous kaolinite, which has been partially or completely removed so that many of the plagioclases show cavities and pits with an etched solution surface, whereas others are still partially filled with a porous kaolinitized feldspar residue. It was impossible to isolate the crystalline fibers to prove whether they were sericite or kaolinite, but the porous character suggests the latter. It is reasonable to assume that the rhyolite porphyry passes transitionally downward into a granite porphyry similar to that just described, and that the kaolinite and calcite in the druses of the rhyolite porphyry have been derived through the partial alteration and leaching of the plagioclase feldspars of such an underlying granite porphyry by thermal carbonated waters of relatively low temperature. This conclusion is in line with the latter part of the statement of Lindgren[1] "In brief, kaolin is never a high temperature mineral but is either a product of alteration by descending waters containing sulphuric acid of carbon dioxide, or of alteration by ascending weak carbonated waters close to the surface."

[1] W. Lindgren, "The Origin of Kaolin," *Econ. Geol.*, Vol. X (1915), p. 90.

EDITORIAL

AN ANCIENT THEORY OF THE PACIFIC

Away back in the last century a wit of Washington noticed that two tall blonde geologists were much together on the streets, that they looked somewhat alike, and were obviously very fond of one another; so he dubbed them "The two Dromios." It "took"—even with the victims. They tried to settle between themselves which was the Dromio of Ephesus and which was the other Dromio; but it was too much for them. So they fell to calling one another simply "The Other Dromio." This was really an improvement on Shakespeare. "The Other Dromio" and "The Other Dromio" were as alike as two peas, as everyone must admit. So thenceforward their letters to one another had the same signature and the last letter that passed between them was signed "The Other Dromio."

Now once upon a time, away back in the last century, these two Dromios were together in the field, and after a long tramp they sat down to rest. Said one Dromio to his mate, "Do you want to know my theory of the Pacific?"

"Certainly," said The Other Dromio, "fire away!"

"Well, sir, in the first place the Moon was pulled out of the west-southwest side of the Earth. In doing this the east side of the crust was badly cracked up. A great zizag crack ran down the west side of Europe and Africa. Europe itself was cracked all to pieces, and stray cracks ran off into Asia and Africa. Europe, as we all know, remains sadly cracked even unto this day.

"The pieces of crust on the west side of the great zigzag crack pushed off as far as they could and have ever since tried to keep out of world-rumpuses of this and all other sorts. This is the gist of my theory of the Pacific Basin and of the Atlantic also." And then he laughed a laugh that scared away the birds.

Then The Other Dromio rose right up and said: "Let's move on."

None the less, he told the story over and over again for years afterward to the boys to whom he lectured, as a clever way to keep them in mind of some of the freak features of the globe.

But the story lost flavor when it was found that the fission theory could not be made to fit the case of the earth and moon (*Carnegie Publication No. 107* (1909), pp. 77–160; summarized on pp. 127–33 and 158–60); and it was dropped. We learn, however, that it has broken out again in a new and virulent form in the land that is alleged to have been most queered by the original catastrophy.

THE OTHER DROMIO

REVIEWS

The Friendly Arctic. By VILHJALMUR STEFANSSON. (With a Foreword by GILBERT GROSVENOR, President of the National Geographic Society, and an Introduction by Rt. Hon. SIR ROBERT BORDEN, Prime Minister of Canada.) Macmillan, 1922. Pp. xxx+784, illustrated.

When the explorer Nansen made the "Fram" fast to an ice floe near the New Siberian Islands and began his zigzagging four years' drift across the northern polar sea, he was pinning his faith to a simple but convincing deduction from observed fact. This was the finding on the west coast of Greenland of driftwood derived from the "Jeannette" which had been crushed in the ice four years before near these islands, so that the course of the driftwood must have been in the pack itself across the frozen sea. The result of his adventure was a splendid vindication of his scientific reasoning, with which, however, those of his colleagues familiar with the facts generally concurred, even though unwilling to stake their lives and their scientific reputations upon it.

Stefansson when he introduced into polar exploration an entirely new method, launching himself boldly out upon the apparently barren Beaufort Sea without adequate supplies and with the necessity of later finding his means of sustenance in the sea itself, he was by so doing setting his own judgment squarely against that of practically all other scientists as well as arctic explorers, and the gauges which he threw down were his life and his scientific reputation. The best proof that his method was believed impracticable is that when nothing was heard from him he was so generally given up for dead.

The Friendly Arctic, in which the account of the latest arctic expedition is now given to the world, is an attempt by this ultra-modest explorer to convince his readers that his achievements were commonplace and required nothing of the extraordinary or heroic; but in spite of this the book is one of the most romantic and gripping to be found in the whole field of arctic adventure, and it has been listed among the best sellers during the summer season. Throughout its nearly 800 pages, the interest never for a moment flags, and one lays down the book feeling that he has come into intimate contact with a remarkable though very human

personality. The book is in reality an autobiography, for in his attempts to put before his readers what he regards as the genial atmosphere of this northern wilderness, he has sought to do it through his own physical, mental, and emotional reactions. In the long list of polar explorers one finds but rarely a man of scientific training. Stefansson is an exception, and the technique of his expedition is throughout an application of modern science quite unhampered by the elaborate conventions of our modern social system. This applies with special force to the vitally important items of diet, shelter, and clothing.

Among the noteworthy achievements of the expedition are included the making known of about 100,000 square miles of the hitherto unknown Arctic, the discovery of three large and a considerable number of smaller land bodies all north of 73° N. latitude; the careful mapping of over 600 miles of new coast line and the correction of the coast lines, the positions and even the character of some of the land areas discovered by Sverdrup; the making of over sixty soundings in widely separated and generally newly discovered portions of the Arctic Ocean; the confirmation of the non-existence of Crockerland; the discovery of a number of coal (lignite) deposits upon the islands of the arctic archipelago; and, especially by the southern party, large collections to show the zoölogy and the botany of the northern coast regions of the continent.

These achievements are the more remarkable by reason of the crushing disaster which almost at the outset overtook the expedition in the loss of the "Karluk," the principal ship of the expedition, together with the major part of its equipment; and perhaps even more important and serious the mutinous behavior of the second in command of the expedition, who was in charge of the southern party, and of others under him. The reviewer is writing this after the case for the mutineers has been stated (in *Science* for July 7, 1922), in which the attempt is further made to show that Stefansson's exploring methods are not new and can be made use of only within extremely limited and favorable districts and for limited seasons only of the year. But it should be clear that the earlier explorers, Rae and Hanbury, who have been cited as sustaining themselves upon the country, both lived in the neighborhood of the coasts, and Stefansson throughout his book has been at much pains to make clear that for the winter season when the light is insufficient for successful hunting, the food must be secured earlier in the season. Likewise, the hides for the clothing and especially for the water-tight boots must be secured at the favorable season.

Lest there should be misunderstanding, Stefansson has stated his case most concisely (p. 5):

Now if it could be demonstrated that food suitable to sustain indefinitely both men and dogs could be secured *anywhere in the polar sea* [italics are mine] then obviously journeys over the ice would cease to be limited either in time or distance. Any part of the polar sea would then become accessible to whoever was willing to undergo the supposed hardships of living on meat exclusively, using nothing but blubber for fuel, and remaining separated from other human beings than his own traveling companions for a period of years.

To demonstrate the feasibility of this . . . . was the main task of our expedition.

We think Mr. Jenness' criticisms along this line may be set at rest by the statement of Admiral Peary, made in the last public address before his death, when, in presenting Stefansson to the members of the National Geographic Society for the award of the Hubbard Gold Medal, he said: "Stefansson has evolved a way to make himself absolutely self-sustaining. He could have lived in the Arctic fifteen and one-half years just as easily as five and one-half years. By combining great natural, physical, and mental ability he has made an absolute record." This statement is to be weighed as not only that of the greatest of polar explorers, but one the plan and technique of whose sledge journeys has been based on the notion that food was unobtainable on the frozen sea way from the coasts.

Stefansson's expedition, officially known as the Canadian Arctic Expedition, carried probably the most elaborate outfit and scientific personnel of any that has ever gone to the arctic. It sailed originally in two ships, the "Karluk" for the geographic (exploring) work, and the "Alaska" for the more detailed scientific work of the southern party in the neighborhood of Coronation Gulf. Later the small vessels "Mary Sachs" and "North Star" were purchased for special work. The expedition was fortunate in having the intimate and cordial personal interest of the Prime Minister of Canada, Sir Robert Borden, who has supported the commander of the expedition in all the trying incidents which developed. In the introduction to *The Friendly Arctic*, written in October, 1921, he says:

The results accomplished by this expedition would have been impossible if Stefansson had been a man of less resource and courage. His commanding intellectual powers, remarkable faculty of observation, capacity for keen analysis of facts and conditions, splendid poise and balance, and immense physical strength and endurance made great results possible. . . . The thanks and appreciation of the Canadian Government have been conveyed to him in a Minute of Council.

With the "Karluk" were carried off most of the sounding apparatus, the sledge chronometers, and the men of especially adventurous

disposition, as well as the better sledges and dogs. The mutiny led by the second in command, which had culminated at Collinson Point, made the preparations for the initial ice trip across the Beaufort Sea several weeks late in starting, and it was this trip which was to test out the plan of the commander. When about to start, a gale of exceptional severity intervened and further held up the departure until the season was so late as to render the expedition hazardous. Shortly after starting out on March 22, 1914, one of the men was severely wounded by a fall and had to be taken back; then two of the best men together with the best dogs who had been sent back with sledge loads but were to rejoin the expedition, were unable to do so owing to a gale and consequent drift of the floes; yet after ninety-three days on the ice the little party of three men made a landing on Banks Island after having traveled about 700 miles over the ice floes and conclusively demonstrated the theory of exploration in the arctic which Stefansson had so persistently advocated in the face of universal opposition. This method was to have many other demonstrations during the more than five years that the expedition remained in the arctic.

Yet a careful reading of this and other parts of the narrative leaves one in little doubt that it is only the exceptional man trained in the technique of seal-hunting and one content to adapt himself to the all-meat diet, who can carry out such an expedition successfully. He must be ready at times to crawl over the floes for hours, lying all the time in ice-cold water in order to stalk the seals necessary for his sustenance, and when on land he must be ready to hunt continuously perhaps for as many days before securing the necessary caribou. In the opinion of the reviewer, Stefansson, in the effort to prove to his readers the friendliness of the arctic to the explorer, has made them see the necessary hardships through his own eyes, those of a quite exceptional shot with the rifle and today the most experienced living craftsman in the technique of arctic travel. His "residence" in the arctic now exceeds that even of Peary, and his continuous "residence" does also. None the less it is true that he has dispelled many illusions quite generally held and has proved the habitability of the northern "barrens" of British America, where a great industry may be developed in meat supply from reindeer and perhaps other herds. The map of the sledge-journeys indicates pretty clearly that the last land masses of the arctic archipelego have now been charted.

A very valuable contribution to our knowledge which has resulted from Stefansson's expedition is the means of preventing or of curing

scurvy, which for a long time was the greatest handicap to polar exploration. Quite contrary to the general view, Stefansson has shown that the antiscorbutic value of certain foods does not lie in their composition, but only in their freshness. Almost any fresh food is an antidote for scurvy, though raw or underdone meat is the most effective. Scurvy is avoided altogether through use of the all-meat diet adopted for the Stefansson expedition.

The book is remarkable well gotten up and is notably free from typographical and other errors. A trifling error is found on page 137, where, in referring to Peary's North Pole sledge-journey, the explorer is made to start from Cape Thomas Hubbard instead of from Cape Columbia. The illustrations are all from photographs but in contrast to most popular accounts of polar adventure, it is the commander only of whom no picture appears.

Whether dealing with the question of scurvy prevention or the technique of snow-house building, of how to stalk the seals or to secure for the larder all the animals in a herd of caribou, the explorer's personality, his scientific methods of thought, his apt illustrations, and his clear and incisive literary style, make the reading of the book fascinating as are few others known to the reviewer. A scrupulous care to do full justice to his subordinates will certainly impress itself upon the reader. If through the accidents of the campaign a sailor in the party has been favored by first sight of a new land, this fact is noted, not only in the diary and in the book, but also in the deposits in the cairns made for future travelers, and in these deposited records the names of all are included.

In the belief of Stefansson these northern lands are destined to have great strategic value as landing stations in the aeroplane routes which in the near future are to connect up the eastern with the western hemispheres across the Arctic Ocean. To many this will appear fantastic, but in an article which has recently appeared in the *National Geographic Magazine* Stefansson appears to have demonstrated the entire feasibility of these routes, and it is easy to see that they must exercise a dominating influence upon the transportation of the future.

William Herbert Hobbs

Annual Progress Report of the Geological Survey of Western Australia for the Year 1921. Perth, 1922.

Pages 1 to 10 give an outline of the work of the Geological Survey since 1896. The remainder of the report (pp. 11–61) deals with the field and office work for the year 1921.

A brief résumé is given of the publications of the Geological Survey, which consist of twenty-five annual reports and eighty-three bulletins. Under the heading "Economic Geology and Ore Deposits," the present condition of knowledge relating to the economic geology of the state is summarized. One of the concrete results of a quarter of a century's work is a geological sketch map of nearly the whole of the state, summing up graphically the work of the survey up to the date of publication, 1920.

The ore deposits of the country are reviewed briefly under individual headings: copper, lead, tin, etc. Aside from gold which, as is well known, has been for many years the greatest mining product of Western Australia, the most important of these appear to be the iron ores, notwithstanding the fact that up to the present their exploitation has been very limited. They are of all grades and of wide distribution. The most noteworthy of the high-grade deposits are those of Yampi Sound, Kimberley division. There are 97,300,000 tons of ore available, two samples of which were found on analysis to contain 65 and 66.5 per cent metallic iron respectively. The close proximity of this deposit to the sea is greatly in favor of its development as a commercial project.

Another important iron ore deposit is that at Wilgie Mia which is almost pure hematite. Analyses of three samples give 68.37, 64.36, and 68.83 per cent metallic iron respectively. There are 27,000,000 tons of ore in sight above the level of the plain and according to borings the ore continues to a depth of 250 feet in places with no appreciable diminution in quality. This deposit is within 40 miles of a railway, and about 200 miles from Geraldton, which is a seaport. Both the Yampi Sound and the Wilgie Mia ores are very low in phosphorus and sulphur and contain only traces of titanium.

Other ores of importance in steel manufacture, namely those of manganese, tungsten, and molybdenum, are present in commercial quantities.

Coals of different geologic ages are known, but mining has been carried on extensively in only one district, the Collie Coalfield, from which 5,000,000 tons have been raised. The coals of the Collie field are sub-bituminous, non-coking coals, which approach very closely to lignite in some parts. The principal consumer has been the railways department. About 10 per cent of the production has been used as bunker coal. The other known coal deposits are chiefly of lower grade. Considerable search for coal has been carried on in the extensive areas of Permo-Carboniferous rocks but unfortunately it has proved fruitless. Apparently the future industrial development of Western Australia is handicapped by scarcity of high-rank coals.

Commercial deposits are known of many of the minor non-metallic minerals but as yet there has been little production. Great interest has been taken in Western Australia in the world-wide search for petroleum but so far there has been no noteworthy development. Two asbestos deposits are described. Chrysotile asbestos of good quality is found at a number of localities over a distance of 200 miles. The fiber compares favorably with that found in any other part of the world with the possible exception of the best Canadian, and although the veins are small the high quality makes it probable that important development will take place.

Under the heading "Some Problems Awaiting Solution," the future work of the Survey is discussed. Among others, the following statement is significant:

> A more thorough investigation than has yet been found possible into those multifarious petrological problems which have such an intimate bearing upon the genesis of the ore deposits of the State, and the conditions which govern their deposition and to a certain degree control the distribution, extent and value of the mineral deposits.

The officers of the Geological Survey of West Australia have done much valuable work in the past and their future contributions to the science will be looked for with keen interest by their brother geologists in other parts of the world.

A. H. B.

Guide Book of the Western United States, Part E. The Denver and Rio Grande Western Route. By MARIUS R. CAMPBELL. Bulletin 707, U.S. Geological Survey, Washington, D.C. Pp. 266, pls. 96, figs. 63, maps 10.

There has recently appeared the fifth part of the well-known *Guide Book of the Western United States* which the U.S. Geological Survey inaugurated at the time of the San Francisco Exposition in 1915. This latest guide, which follows the plan adopted in the earlier bulletins of the series, describes the scenery and treats of the geology of one of the most scenic of the western railway routes. In addition to treating of the tracts immediately adjoining the Denver and Rio Grande Western Railroad between Denver and Salt Lake City, it includes a number of one-day trips that may be made to points of interest from Denver, Colorado Springs, Cañon City, and Salt Lake City.

The book contains a fund of interesting and useful information and is elaborately illustrated with shaded relief maps, halftone plates, diagrams and sections. To the geologist it will prove of value either while traveling by the Denver and Rio Grande, or as a convenient reference book wherein is summarized much of the geology of these portions of Colorado and Utah.

It may be obtained for one dollar from the Superintendent of Documents, Washington, D.C.

R. T. C.

The Shapes of Pebbles. By CHESTER K. WENTWORTH. Bulletin 730 C, U.S. Geological Survey, 1922. Pp. 24, pls. 2, figs. 17. Contains two separate papers entitled "A Method of Measuring and Plotting the Shapes of Pebbles" and "A Field Study of the Shapes of River Pebbles."

The writer of the above papers shows clear appreciation of the importance of the quantitative elements in geology. Such efforts as these are gradually lifting the "study of earth features" from a purely descriptive account to a truly measurable science.

The first of these two papers is essentially an account of the methods employed in determining curvatures of pebbles. Two terms are introduced, (1) the "roundness ratio," or the ratio of the radius of curvature of the sharpest "developed" or secondary edge to the main radius of the pebble, and (2) the "flatness ratio," or the ratio of the radius of curvature in the most convex direction of the flattest "developed" face to the mean radius of the pebble. The measurements are made with a cleverly modified optical convexity gage. The results for each pebble are plotted on logarithmic co-ordinates, applying the "roundness ratio" as ordinate and the "flatness ratio" as abscissa; perfect spheres would thus lie near the upper left corner, angular pieces with reduced facets toward the lower left corner, and pebbles with nearly plane facets toward the lower right corner.

A number of pebbles of different origins (glacial, sandblasted, and river-worn) were thus plotted and the writer was enabled to establish clearly a distinctive grouping with boundary lines for each of these types. There is a slight overlap of glacial and river pebbles, but glacial and sandblasted pebbles are quite distinct. It thus appears that a fairly ready method is available for classifying sediments of large-diameter particles and of uncertain origin. A large number of measurements are

required to secure satisfactory results. The reviewer is interested in seeing what the writer will be able to do along similar lines with regard to that anomaly in form-classification schemes, lake-shingle. It also appears questionable whether, in view of the fact that protuberances are more rapidly worn away in softer rocks, the scheme will not have to be somewhat modified to fit smaller pebbles of softer material.

This very point is, to some extent, met with in the second paper, which is a concrete study of the ratios suggested and the distances traveled by the pebbles. After locating a distinctive bed of quartzite which outcropped in a stream valley, more than 600 pebbles from this bed were collected at intervals downstream from the outcrop. Mileage traveled was plotted against "roundness ratio" for each pebble. For compiling these data the unknown hardness factor, which varied with each pebble, had to be ignored. It was found, however, that the roundness ratio is proportional to the linear size of the pebbles.

After the application of various corrections, the resulting curve was compared with that obtained by "artificial erosion" of pebbles in a motor-driven, water-filled, rotation barrel. It was found that the two corresponded fairly closely.

It seems, then, that the degree of rounding of pebbles may be accepted as a fairly satisfactory means of estimating the distance which this material has traveled. The careful writer points out several minor vitiations of this principle and the reviewer recognizes that these are of importance in the immediate and practical application of the methods here outlined. But he holds that the general scheme outlined above is the clue to much that is yet unsolved in the origin of certain conglomerates and erratics. The Geological Survey is to be commended for aiding such work as is presented in this paper.

C. H. Behre, Jr.

Lehigh University

An Introduction to the Geology of New South Wales. By C. A. Süssmilch. Third edition, revised and enlarged. Pp. 281, figs. 92, tables 5, and folded geological map. Angus & Robertson, Sydney, 1922.

The third edition of this very excellent and useful work has now appeared, eight years after the appearance of the second edition. The principal changes will be found in the chapter on the Carboniferous period, to which notable additions have been made. The Carboniferous

strata of New South Wales are now divided into a lower division of marine origin (Burindi series) and an upper division of terrestrial origin (Kuttung series). In the area immediately north of the Lower Hunter River district these have a total thickness of 14,200 feet. Of especial significance are the glacial tillites and varve shales in the upper portion of the Kuttung series. At least three periods of tillite deposition occurred in the Seaham district; these are separated from one another by two relatively interglacial epochs during which varve shales were deposited in lakes along the margin of an extensive ice front. Further study is bringing to light the fact that the Australian glaciation near the close of the Paleozoic was not confined to the Permo-Carboniferous period, as that is now defined in Australia, but occurred also in the Carboniferous. In the second edition of this work, no mention was made of glaciation in the Carboniferous period.

Following the Carboniferous is the very remarkable Permo-Carboniferous period which presents so many problems of extraordinary interest in Australia. Attaining a maximum thickness of 17,700 feet in New South Wales, the Permo-Carboniferous strata comprise an unusual alternation of thick marine series, extensive coal measures, and glacial beds. This period rightly enough has received more extended treatment than any other.

The book is well printed and well illustrated and gives in concise form just what one wishes to know.

R. T. C.

The Rift Valleys and the Geology of East Africa. By J. W. GREGORY. Pp. 479, pls. 20, figs. 44. Seeley, Service & Co., Ltd., London, 1921.

In this work Professor Gregory has assembled much of what is known of the geology of a very significant portion of the African continent. As the title indicates, the outstanding feature is the Great Rift Valley, or zones of rifting, in which essentially parallel fracturing has taken place on a vast scale. In East Africa the main fault trench, about 40 miles wide, is bordered by prominent boundary faults which in some places form steep single scarps and in some other places cause a succession of steps. On the floor of the trench a great number of lesser faults run nearly north and south approximately parallel to the master bordering fractures. Lakes abound on the floor of the trench.

The chief value of the book in the opinion of the reviewer lies in its descriptive geology, for one may well receive the assigned cause of the

rifting and its relation to contemporary earth movements with reservation. At the end is a valuable bibliography amounting to thirty pages.

R. T. C.

Notes on the Geology of New Zealand. (To accompany Geological Sketch Maps.) By P. G. Morgan. *New Zealand Journal of Science and Technology*, Vol. V, No. 1, pp. 46–57. Wellington, N.Z., 1922.

In this article, from the *New Zealand Journal of Science and Technology*, the author has given a brief outline of the areal geology of New Zealand so far as it is known. The geological maps in black and white which the notes are to accompany have been compiled from a number of maps made at different times and by various geologists. The extraordinarily complicated structure and the fact that New Zealand geologists have differed greatly on vital points have made the task a difficult one. The European time scale has been used to make the maps more intelligible to geologists of other countries, but the New Zealand divisions correspond only roughly with the European divisions.

Certain schists, gneisses, and limestones in the South Island have been considered of Archean age but contain intrusives which may be as late as Early Triassic. About one-fifth of the area of the South Island is classed as "undifferentiated and doubtful Paleozoic." There are five small areas known where the strata contain recognizable fossils and the oldest of these faunas is of Lower Ordovician age. Much careful and highly detailed work will be required to make a reasonably accurate map of the Paleozoic strata. The lack of fossils and the intense folding will make this a formidable undertaking. The great and widespread dynamo-metamorphism of certain of these rocks suggests that there were important periods of diastrophism in Pre-Cambrian and Paleozoic times. No Paleozoic rocks have yet been found on the North Island.

Mesozoic rocks are well represented in both the North and South Islands. The early and middle Mesozoic strata fall into one great Trias-Jura series (the Hokanui system). They are all involved in a great post-Jurassic or post-Hokanui deformation. The Middle and Upper Cretaceous strata which follow are separated from those below by a strong and widespread angular unconformity. This unconformity marks by far the greatest break in the known geologic history of New Zealand and had the time scale grown up there instead of in Europe it would

undoubtedly delineate eras rather than periods. Previously the foreshore of Gondwanaland, New Zealand may be said to have begun an independent existence with the post-Hokanui deformation.

There is a stratigraphic and paleontologic break between the Upper Cretaceous and the Tertiary. Tertiary rocks occupy a considerable area on the North Island. The Tertiary periods in New Zealand are noted for their intense vulcanism. The later volcanic rocks contain quartz veins which have yielded many million ounces of gold and silver.

A. H. B.

Phytopaläontologie und Geologie. By Dr. W. Deecke. Berlin: Verlag von Gebrüder Borntraeger, W35, Schöneberger Ufer 12a, 1922. Pp. 97.

Professor Deecke is not a specialist in paleobotany, but writes from a general paleontological point of view. The book summarizes our present knowledge on the geological importance of fossil plants rather than attempting to approach any of these problems on the basis of intimate familiarity with paleobotany.

In spite of this drawback, the book is useful to anybody who wishes a summary of such questions as the importance of marine algae, or the influence of plants on rock formation, or the relative importance of autochthony and allochthony, especially with reference to the formation of coal seams. Another problem, the importance of plants as climatic indicators, has been so much discussed in the last years, that very little can be said about it without constant repetition of familiar ideas.

An interesting chapter is the discussion of plants as index fossils, and Deecke comes to the conclusion that plants are not suitable for a general classification of formations, but rather for the differentiations of horizons in a few periods like the Carboniferous. Plants are especially valuable for index fossils in the determination of local horizons, and have been properly used for such purposes in the Upper Cretaceous and Upper Miocene as well as in the Coal Measures.

Deecke has used extensively the German, Scandinavian, French, English, and American literature. It is only natural that the latter three literatures should not have been fully utilized for the last eight years since, during the war and even after the war, such literature was not always accessible to German scholars, first, on account of their isolation during the hostilities, and afterward, on account of the difficulty of buying foreign literature with devaluated marks.

A. C. Noé

The Upper Cretaceous Gastropods of New Zealand. By O. WILCKENS. New Zealand Department of Mines. Geological Survey Branch. Palaeontological Bulletin No. 9. Wellington, N.Z., 1922.

Die Ursachen der diluvialen Aufschotterung und Erosion. Von W. SOERGEL. Berlin: Gebrüder Borntraeger, 1921. (Price, 18 M.)

Verwertung Geologischer Karten und Profile. Zweite Auflage. Von FR. SCHÖNDORF. Berlin: Gebrüder Borntraeger, 1922.

La Géologie du Pétrole et la Recherche des Gisements Pétroliferes en Algérie. Par MARIUS DALLONI. Alger: Jules Carbonel, Imprimeur Libraire-Éditeur, 1922. (Avec 48 figures dans le texte et une carte.)

Geologic Reconnaissance of the Pidatan Oil Field, Cotabato Province, Mindanao. By WARREN D. SMITH. The *Philippine Journal of Science,* Vol. XX, No. 1. Manila, 1922.

On the Correlation between the Fluvial Deposits of the Lower-Rhine and the Lower-Meuse in the Netherlands and the Glacial Phenomena in the Alps and Scandinavia. By J. VAN BAREN. With 20 plates, 3 sketches, and map. Mededeelingen van de Landbouw-Hoogeschool, Vol. XXIII, No. 1. H. Veenman, Wageningen, 1922.

Review of Philippine Paleontology. By ROY E. DICKERSON. The *Philippine Journal of Science,* Vol. XX, No. 2. Manila, 1922.

Report of the State Geologist on the Mineral Industries and Geology of Vermont, 1919–1920. Pp. 332, pls. 47, figs. 24.

The report comprises a number of papers by various authors on different phases of the geology, and mineral resources and industry of the state. These are:

"The Structural and Metamorphic Geology of the Hanover District, New Hampshire," by J. W. MERRITT: The area studied lies entirely in New Hampshire but is part of a larger area of similar character

extending westward into Vermont. The field work is supplemented by a quantitative chemical and mineralogical study of the schists and granite of the region, leading the author to the conclusion that the schists are of sedimentary origin.

"A Contribution to the Geology of Essex County, Vermont," by Rolf A. Schroeder: A study of the occurrence and possible commercial exploitation of the Averill granite as a building stone.

"Notes on the Areal and Structural Geology of a Portion of the Western Flank of the Green Mountain Range," by Nelson C. Dale: An investigation of the more mountainous portions of Middlebury and Burlington Quadrangles, the geology including highly folded and faulted, thoroughly metamorphosed, Cambrian and Pre-Cambrian sediments.

"The Geology and Mineralogy of Braintree, Vermont," by Charles H. Richardson and Charles K. Cabeen: Of interest is the discovery of new graptolitic beds in the slates of Braintree and Rudolph proving the southward extension of the Memphremagog slates in Braintree and Rudolph to be early Ordovician.

"A Detailed Study of the Trenton Beds of Grand Isle," by George H. Perkins, and "A Report on the Fossils of the So-Called Trenton and Utica Beds of Grand Isle, Vermont," by Rudolph Ruedemann. Professor Perkins describes the distribution and character of the Trenton beds of this locality and calls attention to the fact that the so-called Utica beds present are but a portion of the Trenton. Dr. Ruedemann supplements this paper with a discussion of the paleontology in which faunal comparisons are made with the Trenton of New York and other regions. The limestone he finds to correspond with the Glen Falls division or basal Trenton, of New York, while the black shales are referred to the Canajoharie shale of the same state, and in part also to the Snake Hill division, or Schenectady beds. He comes to the conclusion that the Ordovician is represented in Vermont by beds probably no younger than the Trenton.

"Progress in Talc Production," by Elbridge C. Jacobs: There is an increased demand for talc due to substitution of the domestic material for the foreign product, and increase in the number of uses to which it is put. A complete list of known uses of talc is given, reprinted from a United States Bureau of Mines Bulletin.

"Studies in the Geology of Western Vermont," by Clarence E. Gordon: A detailed description of the physiography, stratigraphy, and structure of an extensive area in Western Vermont. A bibliography is appended.

"The Geology of Lake Willoughby," by Elbridge C. Jacobs: Mr. Jacobs concludes that Lake Willoughby is a glacial lake, 1,164 feet above sea level, occupying in part a glacially fashioned trough, which originated probably as a graben. A gorge in the bottom of the lake is believed to be due to glacial cutting. The mountains on either side are composed of Ordovician limestones and phyllites intruded by granite.

"Mineral Resources," by G. H. Perkins: The author finds that prosperous conditions exist in the mineral industries of the state.

A. C. McF.

OLUME XXXI NUMBER 3

THE JOURNAL OF GEOLOGY

A SEMI-QUARTERLY

APRIL-MAY 1923

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Among articles to appear in early numbers of the *Journal of Geology* are the following:

The Pleistocene of Northwestern Illinois: a Graphic Presentation of the Chief Lines of Evidence. By MORRIS M. LEIGHTON.

Tilted Galena Dolomite over Fossiliferous Loess at the Border of Belvidere Lobe in Winnebago County, Illinois. By MORRIS M. LEIGHTON.

The Physical Chemistry of the Crystallization and Magmatic Differentiation of Igneous Rocks. VIII. By J. H. L. VOGT.

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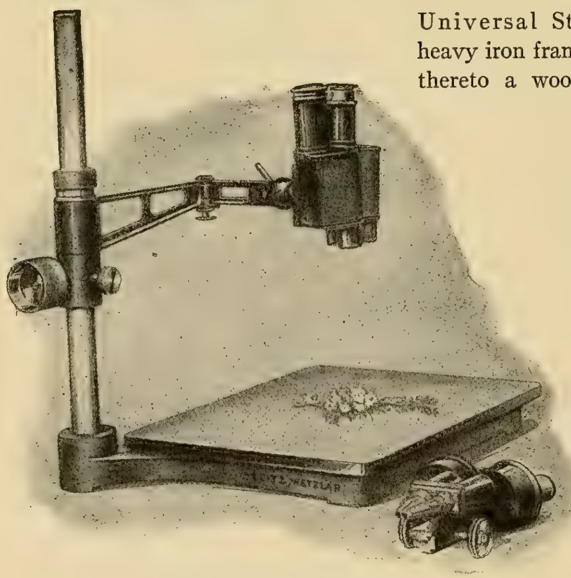

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THE

JOURNAL OF GEOLOGY

April-May 1923

THE FINAL CONSOLIDATION PHENOMENA IN THE CRYSTALLIZATION OF IGNEOUS ROCK

R. J. COLONY
Columbia University, New York City

Pyrogenetic processes may, for convenience, be divided into (*a*) effects produced within the igneous rock mass itself, and (*b*) effects produced by the end-stage consolidation products (aqueo-igneous matters) upon the neighboring rocks into which these matters have been forced.

The effects produced within the igneous rock itself are due in part to molecular changes taking place in the various individual minerals which crystallize during consolidation, some of them possessing one or more different allotropic forms into which they pass as the temperature of the rock-mass falls through the various critical ranges where such inversions are effected; in part to actual reactions occurring between some of the component minerals of the rock already crystallized and the remaining still-molten magma;[1] and in part to reactions due to adjustments of equilibrium between the extreme end-stage, highly concentrated "mother-liquor" which, by selective freezing, has been enriched with the more volatile gases usually termed "mineralizers," among which water

[1] N. L. Bowen, "The Reaction Principle in Petrogenesis," *Jour. Geol.*, Vol. XXX (1922), pp. 177–98.

plays an important part, and the now almost wholly consolidated rock. These equilibrium adjustments, and the changes produced by chemical attack, may be thought of as an extension of the reaction effects described by Bowen. At this stage much of the quartz and some of the alkalies, especially soda in such form as to appear ultimately as albite, seem to be concentrated in the form of a liquid consolidation-residuum, which, from such evidence as is presented in the rocks themselves, must possess an extremely low viscosity, great penetrating power, and considerable chemical activity.

During the consolidation of plutonic rocks especially, the mineralizers operate to effect changes in some of the already formed minerals, and in some cases cause profound changes in the rock itself. When present to only a small extent their effects are usually confined to the parent igneous rock. This is exhibited in various ways. Frequently the end-phase products, quartz and albite, penetrate the earlier feldspars, converting earlier orthoclase into a sort of "injection perthite," beautifully exhibited in a granite near Fort Ann, New York, and illustrated by Figure 1. In this granite each feldspar grain is surrounded by a narrow rim or border of quartz and albite, which likewise penetrate the grains irregularly and form also veinlets of microscopic dimensions in the rock. Lying in and associated with such veinlets is a little graphite, which apparently is of the same origin as the end-stage material itself. The rock carries a little orthorhombic pyroxene as one of the ferromagnesian components and this, wherever it appears, has been converted to serpentine, which is here an end-stage reaction product originating partly because of changes in equilibrium, and partly because of hydration during the last stages of crystallization of the rock.

Sederholm[1] describes as "deuteric effects" certain products occurring as an intergrowth of two minerals at their contacts by reason of the action of magmatic end-stage emanations; but the structures thus described are very minute. The writer has extended the term to cover all magmatic end-stage emanation phenomena,

[1] J. J. Sederholm, "Synantetic Minerals and Related Phenomena," *Bull. de la Com. Geol. de Finlande*, No. 48.

which frequently cause large-scale changes and very profound effects, especially in the way of mineralization.

Another illustration of the same process is shown in Figures 2 and 3. In this case the rock, a diorite from Newfoundland, is self-injected in the same manner, but the effects are more profound. The original ferromagnesian mineral has been wholly converted to a

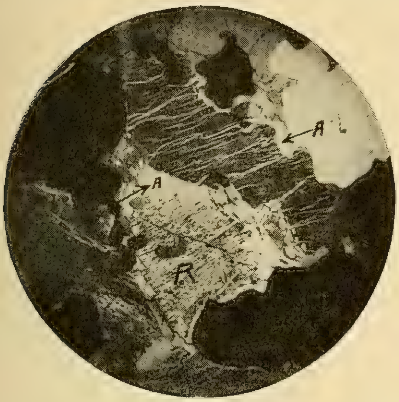

FIG. 1

FIG. 2

FIG. 1.—Photomicrograph of deuterized granite, Fort Ann, New York. Nicols crossed, magnification 20 diameters. The earlier feldspar is orthoclase, which has been heavily injected with end-stage consolidation products consisting of quartz and albite (*A*). These products are both interstitial, and injected through the rock, on a microscopic scale. The black grains are quartz at the position of extinction. A crystal of orthorhombic pyroxene (*P*) has been converted to serpentine by the same agents and during the last stages of crystallization.

FIG. 2.—Photomicrograph of diorite from Newfoundland. Nicols crossed, magnification 20 diameters. Coarsely granitoid in texture; the single large crystal (dark gray) is an earlier plagioclase feldspar of andesine composition thoroughly injected with end-stage quartz and albite. Connected with this stage and because of changes in equilibrium, together with hydration effects, the ferromagnesian mineral (*A*) has been converted to an interlacing mat of actinolite needles.

complex of matted actinolite needles and the plagioclase, otherwise quite fresh and unaltered, has been thoroughly injected and soaked with quartz and albite; changes obviously connected with end-stage emanation products of a dioritic magma.

Even in more basic rocks such phenomena are common where the mass is of sufficient extent to have permitted more or less crystallization-differentiation. In the diabase which forms the

palisades along the Hudson River in New Jersey and New York, the usually resistant aluminous augite has been affected by precisely similar processes, so that in places it is partly converted into a complex of green hornblende (almost actinolite), brown biotite and magnetite dust, frequently associated with end-stage quartz. A quartz-rich phase is found near the top of the same intruded sheet, quartz usually occurring in coarse micrographic intergrowths

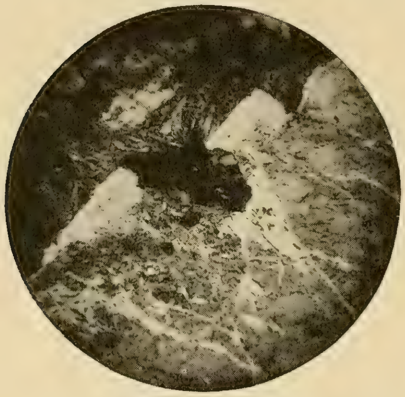

FIG. 3

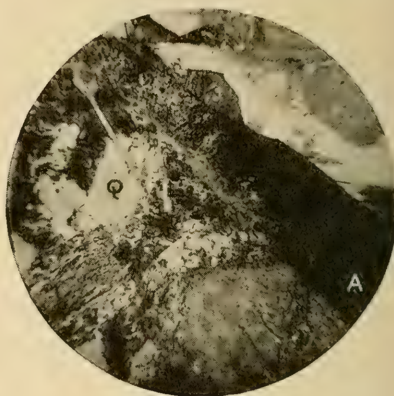

FIG. 4

FIG. 3.—Photomicrograph of diorite from Newfoundland. The same rock shown in Figure 2, but taken from another part of the thin section. Nicols crossed, magnification 20 diameters. The acicular aggregate is actinolite. Note the way in which the late-stage product (white) injects the plagioclase (gray).

FIG. 4.—Photomicrograph of Palisades diabase. Nicols crossed, magnification 20 diameters. An augite crystal (*A*) with pinacoidal parting indistinctly shown, has been partly converted to a complex of actinolite, magnetite, chlorite and biotite. Quartz (*Q*) of late-stage crystallization is in contact with the augite. Illustrative of equilibrium changes due to reaction effects between the quartz-alkali rich final consolidation product and earlier formed crystals.

with orthoclase. This is illustrated in Figure 4; an augite crystal (*A*), showing indistinctly pinacoidal parting, has been in part converted to a complex of actinolitic hornblende, biotite, magnetite, and chlorite; end-stage quartz (*Q*) is associated with these products, and it seems reasonable to conclude that the quartz-rich alkali-rich liquid residuum must have been responsible for the chemical changes involved, together with equilibrium changes occurring because of the different conditions of temperature and concentration.

Olivine and magnesia-rich pyroxenes are particularly susceptible to magmatic end-stage products. Peridotites, olivine-rich pyroxenites and dunites thus are converted to great masses of serpentine; not by "weathering," but during cooling and final consolidation.

This was recognized many years ago by De Launay[1] during his studies of ore deposits, and expressed as follows:

> Il resterait, d'alleurs, á examiner si cette serpentinisation même n'est pas souvent contemporaine de la cristallisation (comme paraitrait le prouver sa persistance à de très grandes profondeurs) et si elle n'a pas été produite par un excès de vapeur d'eau, dont la presence, dans le magma fondu, aurait pu, en même temps, faciliter la concentration metallique.

Where basic magmas are involved, crystallization-differentiation may concentrate sufficient quantities of the more acid end-stage products to cause profound changes to take place and to produce ore-bodies of magnitude and commercial importance. The nickeliferous "norites" of the Sudbury region in Ontario, and the Maskwa River norite in Manitoba are examples of such large-scale effects. The "norites" of these areas have been so extensively changed that in many instances they do not resemble true norites either mineralogically or chemically. Their pyroxene has been converted to actinolite and biotite, their feldspar have in some cases been albitized, and in places they have been swamped in end-stage quartz and heavily mineralized. Figures 5, 6, and 7 illustrate some of these changes.

One of the curious results of the conversion of pyroxene to actinolitic hornblende is exhibited in the powerful penetrating capacity developed by the uralitized pyroxene, since it is commonly found in an aggregate of acicular crystals which frequently penetrate the adjoining feldspars in every direction; soda seems to have been added during the process, derived undoubtedly from the soda-enriched liquid residuum responsible in part for the conversion. In some cases sufficient soda has been acquired by the uralitized pyroxene to cause the production of a blue amphibole of about the quality of glaucophane (norite from the Creighton Mine).

All stages of flooding with the end-consolidation, more siliceous, aqueo-igneous concentration-product may be seen, the maximum

[1] H. L. De Launay, *Contributions a L'Etude des Gites Metalliferes*, 1897, p. 25.

effects producing the so-called "micropegmatites," which are essentially the consolidated "concentrates" themselves—the "acid" differentiate of the more basic portions of the magma. These rocks consist of alkalic feldspars, biotite and hornblende, engulfed in a matrix composed of a micrographic intergrowth of quartz and alkali feldspar, which sometimes comprises 50 per cent of the rock.

FIG. 5

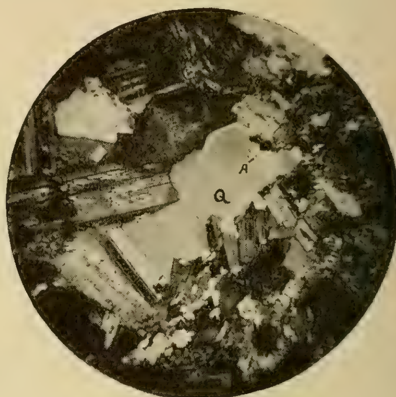

FIG. 6

FIG. 5.—Photomicrograph of norite from the Sudbury region, near Windy Lake, Ontario. Nicols crossed, magnification 20 diameters. The orthorhombic pyroxene here has been almost wholly converted to serpentine (Bastite) (*S*). A small amount of end-stage quartz (*Q*), in places mixed with feldspar in micrographic intergrowth (*M*) is usually associated with, or in proximity to, the serpentinized pyroxene. The feldspars in this facies of the norite have been but very slightly affected by hydrothermal attack, carrying very sparingly distributed small patches of sericite here and there.

FIG. 6.—Photomicrograph of norite from the vicinity of the Blezard Mine, Sudbury region, Ontario. Nicols crossed, magnification 20 diameters. Carrying considerable end-stage quartz (*Q*) and showing albitization margins (*A*) on some of the feldspar. The orthorhombic pyroxene has been almost wholly converted to pale green actinolitic hornblende, grading into biotite in places, remarkably ragged and patchy, and penetrating the feldspar in many places.

The biotite has been changed to chlorite, at times spherulitic; the hornblende is actinolitic in character, suggesting derivation from some other original.

In places the quartz increases in quantity so that it forms large groups of crystals of considerable area, but related nevertheless to the very end-stages of consolidation, judging from its structural relations to the other minerals. The phenomena described may all

be connected with late-stage crystallization; the coarsely micrographic matrix, which has the general characteristics of a quartz-feldspar eutectic, the chloritization of the biotite and "actinolitization" of the hornblende (or the uralitization of an original pyroxene) are all products of the activity of a solution-residuum formed in relatively large quantities during the selective crystallization of a much more basic magma. Figures No. 8 and 9 are illustrative

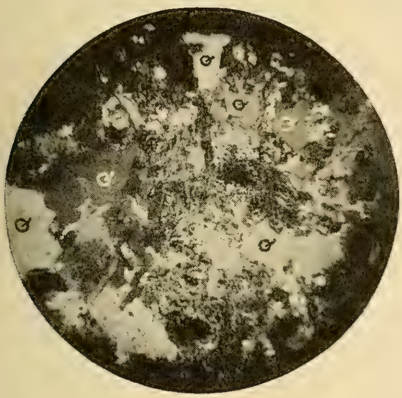

FIG. 7

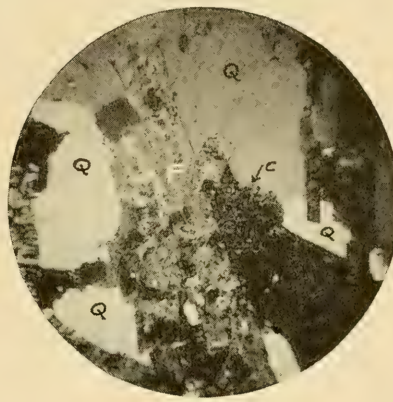

FIG. 8

FIG. 7.—Photomicrograph of norite from the Creighton Mine, Sudbury, Ontario. Nicols crossed, magnification 20 diameters. Swamped in end-stage quartz (*Q*) which in places had flooded the rock. The original orthorhombic pyroxene almost wholly uralitized and reorganized; considerable soda has been added in the processes so that in places a blue amphibole of about the quality of glaucophane has been formed, grading into the commoner green actinolitic hornblende. This rock has been more profoundly affected than the one shown in Figure 6.

FIG. 8.—Photomicrograph of micropegmatite from the acid margin of the nickel eruptive, Sudbury district, Ontario. Nicols crossed, magnification 20 diameters. Showing quartz in large crystal units (*Q*), albitized feldspar (*F*), and spherulitic chlorite (*C*), derived from biotite. The character of the rock is dependent on end-stage crystallization processes.

of this particular phase of late-stage crystallization. Both are "micropegmatites" from the Sudbury region, taken from the acid border of the nickel eruptive.

Figure 8 shows the larger crystal units of quartz flooding earlier feldspar, which has been albitized, and spherulitic chlorite, derived from biotite. Figure 9 shows the coarsely micrographic intergrowth of feldspar and quartz; the ferromagnesians have

been similarly affected, with the production of acicular green hornblende.

The action of end-stage emanation products on rocks which igneous masses have invaded may be even more extensive and profound. The extent and magnitude of these metamorphic changes depend upon the character of the rocks intruded and upon the quantity and quality of the emanation products themselves.

FIG. 9

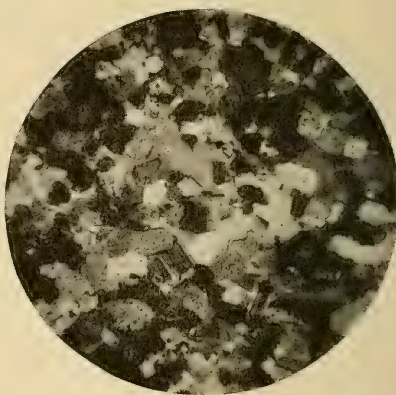

FIG. 10

FIG. 9.—Photomicrograph of micropegmatite, Levak Siding, near Windy Lake, Sudbury district, Ontario. Nicols crossed, magnification 20 diameters. Showing coarsely micrographic intergrowths of end-stage crystallization. Actinolitic hornblende in center, passing into chloritic aggregates.

FIG. 10.—Photomicrograph of arkose, adjacent to the Palisades diabase, about four miles south of Alpine. Nicols crossed, magnification 20 diameters. The "detached," or slightly separated (not all of the grains are as distinctly separated as here shown, however), and more or less reorganized and original clastic grains of feldspar are shown set in a matrix of coarser unit grains of mosaic-like quartz. The dark or black areas are quartz units in the position of extinction.

All of the contact phenomena are directly related to the action of magmatic end-stage emanations which produce a bewildering series of silication, sericitization, chloritization, epidotization, carbonatization, silicification, garnetization and metallic-mineralization effects whose origin and significance were recognized long ago by Lindgren, Kemp, Spurr, Berkey, and many others, and which are beyond the scope of this paper to discuss.

It has not been generally recognized, however, that such enormous quantities of quartz and feldspar may be concentrated by the

crystallization-differentiation of batholithic masses as to serve as carriers for magnetite, and to act at the same time as granitizing agents and producers of magnetite-ore bodies.[1] In these cases the country-rock may be so flooded with quartz, or quartz and feldspar from igneous sources, as to profoundly change the character of the invaded rocks without causing any of the phenomena just mentioned to ensue. As an example of this action on a very small scale, the effect of the intrusion of the Palisades diabase on some portion of the adjacent arkose may be mentioned. The original clastic grains of feldspar seem to have been detached and in small part recrystallized, the original grains of quartz appear to have been merged with and taken into the substance of the invading end-stage quartz derived from the igneous mass itself, so that the feldspar grains of the arkose are set, in a sort of poikilitic fashion, in a matrix of much more coarsely crystalline quartz behaving as a mosaic of larger unit grains. An attempt has been made to show this in Figure 10.

In connection with the magnetite ore-bodies of southeastern New York, there is an occurrence of extremely coarse and very acid granite, always intimately associated with the ore-bodies and usually best and most extensively developed immediately adjacent to them. Field and petrographic study shows that these "granites," which the writer has called Pochuck granite, are merely end-stage quartz, with in some cases feldspar, carrying partially assimilated fragments of the country rock (Pochuck-Grenville), and representing the very extreme end-phase product of the same general processes which produced the magnetite. Figures 11 and 12 illustrate two of them; Figure 11 is from the vicinity of the Clove mine, Figure 12 is adjacent to the Forest of Dean Mine, Orange County, New York. Both samples were taken at the surface. It will be observed that they are very largely quartz with a few scattered, partially assimilated fragments of country-rock (Pochuck-Grenville). Where the Pochuck-Grenville was more calcareous, and especially where the emanations encountered actual interbedded limestone (Grenville), characteristic lime-contact minerals were formed, although the interbedded limestone itself may have

[1] R. J. Colony, *The Magnetite Deposits of Southeastern New York.* To be published as a bulletin of the New York State Museum.

been totally destroyed. Such relations are shown in the old Mahopac, Tilly Foster, O'Neill, Forshee, Redback, Standish, Croft, and Todd mines in Orange and Putnam counties, New York.

It seems evident, therefore, that the injection of an igneous mass into pre-existing rock, and its subsequent consolidation, sets into motion physical and chemical processes which produce a

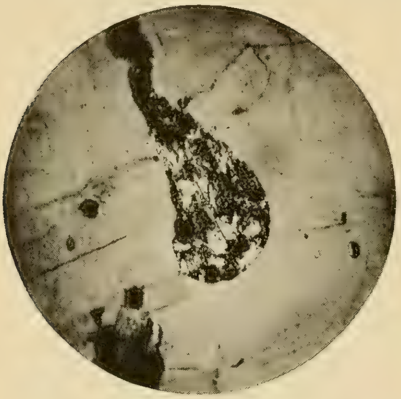

FIG. 11

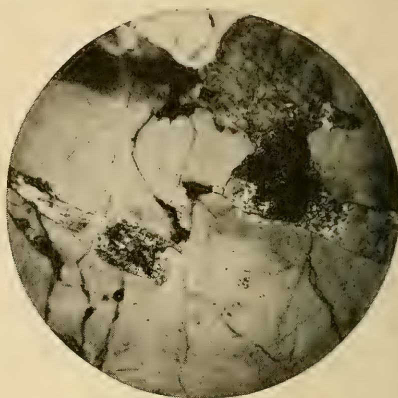

FIG. 12

FIG. 11.—Photomicrograph of Pochuck granite, Clove Mine, Orange County, New York. Nicols crossed, magnification 20 diameters. The gray field is a large unit grain of quartz. Swamped in the quartz is a serpentinized remnant of Pochuck-Grenville, consisting of an orthorhombic pyroxene with attached and sericitized feldspar. Practically all of the minerals other than quartz are simply remnants of partially assimilated fragments of like type, all profoundly affected by the magmatic end-stage aqueo-igneous solutions which gave birth to the quartz.

FIG. 12.—Photomicrograph of Pochuck granite, Forest of Dean Mine, Orange County, New York. Nicols crossed, magnification 20 diameters. An extremely coarse, grayish-white granite made up of end-stage quartz and feldspar with partially assimilated fragments of Pochuck-Grenville. The gray field is quartz, the fragments are remnants of country rock.

startling array of progressive changes,[1] both in the parent body and in the rock invaded. In many cases the effects are profound and of the utmost economic importance, since not only are most metalliferous deposits connected directly or indirectly with such processes, but many substances used in the arts and industries have their origin in the same sources.

[1] A recent article by Bowen on the behavior of inclusions in igneous magmas, which appears in a supplement to *Journal of Geology*, No. 6, Vol. XXX (1922), deals with some of the changes, which are explained on the basis of the "reaction principle."

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Warm climates within the polar circles and glacial climates on the borders of the tropics are justly regarded as the most outstanding features of geologic climates. That these contrasted climates should have intervened between one another to form an oscillating series adds a feature of the first order of significance. The glaciations on the borders of the tropics seem at first thought the more remarkable, and perhaps they are so, but when it is considered that five miles of ascent brings a greater fall of temperature than a change of 3,000 miles in latitude, there is reason to raise the question whether the transfer of low-latitude warmth to high latitudes is not after all the weightier feature. However this may be, mild climates in high latitudes are features of the highest order of interest.

Now for more than half a century it has been widely maintained that an extension of the sea would at least help explain the mild climates in high latitudes, if indeed it would not furnish a full explanation. In addition to this particular application, the doctrine that sea extension contributes to warmth of climate has found many other expressions in geologic literature.

This habitual association of warmth with sea extension seems to have grown out of the earlier view that in primitive times a warm ocean covered the whole earth. Starting with this concept, the differentiation of climates was held to have grown gradually out of universal warmth by general cooling attended by the emergence of the land and the reduction of the sea surface. The association of the sea with warmth and the land with lower temperature was natural under these assumptions.

When the study of the widespread phases of glaciation began—about a century ago—a general extension of glaciation was only

known to have occurred at a late geological period, and so it was natural to assign it to an advanced stage of cooling of the earth. Further, it was seen to be correlated with the great deserts and so the phenomena of glaciation and of great aridity were thought to be but the signs of a senile planet; the advance stages of the final drying up and freezing up of the earth. Thus the sea and warmth were habitually associated in geologic thought about the earlier ages, while dryness and cold were close companions in the thought of the later stages.

Who first advanced the special doctrine that the mild climates of the geologic ages in high latitudes were caused by an extension of the sea, it would be venturesome to state. Very likely it grew up gradually by little transfers of the earlier thought of a universal warm sea to the special cases of warm climates in high latitudes as evidences of these came successively into notice. At any rate, if the doctrine is to be put on the shelf, it is perhaps just as well not to lay stress on its parentage or on its clientele. It was a common doctrine, and quite unchallenged, when I first became interested in paleoclimatic subjects; I accepted it as standard doctrine and taught it. It was only when I had occasion to inquire seriously into geoclimatic problems that doubt as to its verity arose.

To avoid ambiguity let it be noted at the outset that the question here raised is specific and definite. Would an extension of the sea in high latitudes cause or tend to cause a warm climate *in and of itself irrespective of superimposed factors*? Of course the extension of a *warm* sea would favor a warm climate, and the extension of a *cold* sea, a cold climate. Our question is whether the replacement of a normal land surface by a normal sea surface in the high latitudes would thereby, irrespective of special conditions, tend to give a warmer climate. Let us first look for concrete evidence, and later turn to the theory of the case.

COMPARISON OF THE CLIMATES OF THE WATER-HEMISPHERE WITH THOSE OF THE LAND-HEMISPHERE

The distribution of sea and land is fairly well suited for this inquiry. The Southern Hemisphere is very largely covered by the ocean; its land surface is not only much smaller than the sea

surface, but is divided into tracts so well separated from one another and so nearly surrounded by the sea that they show the sea's normal influence. There is only just about enough land to bring out the normal effects of the sea influence satisfactorily under present conditions.

The Northern Hemisphere, on the contrary, has more nearly equal areas of land and of sea, but there is a distribution of these that helps us in distinguishing their individual influences. Viewed from the North Pole, the center of cold of this hemisphere, the land is seen to surround it in the form of a great triangle of which Africa and Asia form the base and North America the apex. Most of what sea there is in the Northern Hemisphere lies outside this triangle and in two parts, the North Atlantic and the North Pacific. The North Pacific is broadly connected with the South Pacific and may be regarded as an outlying adjunct of the water hemisphere on the south.[1] The connection of the North Atlantic with the South Atlantic is much narrower and their relations much less intimate, for the protruding eastern angle of South America splits the equatorial current and measurably differentiates the two oceans. The North Atlantic is very much more nearly surrounded by land than the North Pacific and its mean temperature is also higher than that of the other oceans.

Into the triangle of land about the North Pole there penetrate several offshoots or dependencies of the main oceanic bodies. These are land-girt in varying ways and degrees and these relationships help to show the climatic effects of certain special relations of land and sea, as will appear later. The dependencies of the North Atlantic connect it with the North Polar Sea—scarcely worthy of being called an ocean—which immediately surrounds the North Pole.

Comparison of the hemispheres as a whole.—As is well known, the Southern or Oceanic Hemisphere has a distinctly cooler and more inhospitable climate than the Northern Hemisphere, in which land is a much larger factor. This may be verified to any desired degree

[1] The North Pacific is always included in the technical "Water Hemisphere." This stands oblique to the climatic zones and on that account cannot well be used in a brief comparison of climatic hemispheres.

by specific comparisons of the temperature charts, the positions of the isothermal lines and the distribution of life. The general import is most conveniently indicated by the fact that the *thermal* Equator lies 5° or 6° north of the geodetic or geographic Equator. Krümmel estimates the average surface temperature in the Northern Hemisphere to be 19.20° C., that in the Southern to be 15.97° C.; while the air temperature averages 15.1° C. for the Northern Hemisphere, and 13.6° C. for the Southern.[1]

For the purposes of this discussion, the nature and distribution of life furnish better criteria than simple temperatures, since the evidences of past climates rest almost wholly upon the fossil life, and anyway life is a composite index of climate—a natural correlation as it were—while temperature is only one factor. For brevity, then—as well as its comprehensive significance—life, especially human life, will be used mainly in the following comparisons. Human life implies the concurrent presence of a highly complex series of supporting types of lower life, both vegetable and animal.

COMPARISONS ON SELECTED PARALLELS OF LATITUDE

To sweep the full range of the high latitudes, let us begin our comparisons with the parallels of 50° on each side of the Equator. Let us begin also at the most typical spots. The Indian Ocean has a form and a placement specially well suited for showing whatever warming effects in mid-latitude a great expanse of sea may have. Its northern edge reaches 20° beyond the Equator and thus brings in from the Northern Hemisphere a large section of equatorially warmed water, while the southern edge falls more than 20° short of the South Pole and thus excludes a large area that might otherwise contribute polar waters. Furthermore the Indian Ocean is broad and roughly rotund. Its connections and relations are simpler than those of the other great oceans. Let us then start our comparisons with an island lying centrally in this highly representative ocean. Kerguelen Island lies a little on the equatorial side of 50° S. Lat. (48°39′ to 49°44′), in the very heart of this ocean, far away from any other land of moment. It is more than 2,000 miles from Africa and a little farther than this from Australia; it is more

[1] Cited from *A Textbook on Oceanography*, by J. T. Jenkins, London, 1921.

than 1,000 miles from the nearest known land to the south and 3,800 miles from the nearest land on the north. It is therefore typically oceanic. The severity and sterility of its climate are so pronounced that it stands as a type of inhospitality. Its mean temperature is only about 39° F.(4° C.). Bearing directly on the question here at issue, the *Encyclopedia Britannica* says: "Its temperature is kept down by the surrounding vast expanse of sea." Relative to its discoverer, Yves Joseph de Kerguelen Tremaric, it further says: "He was one of those explorers who had been attracted by the belief in a rich southern land, and this island, the South France of his first discovery, was afterwards called by him, 'Desolation Land' in his disappointment."

For comparison with this southern land of desolation in the heart of a typical ocean, let us follow the same meridian to the same latitude in the Northern Hemisphere. It leads to a point in Central Asia, the heart of the earth's greatest continent, and is thus admirably adapted to our purpose. The comparison point lies about 350 miles south of the Trans-Siberian Railway. The region has long been inhabited and has played a notable part in human history. In its habitability, it is in strong contrast with Kerguelen. The region habitable for man in the Northern Hemisphere extends about 1,400 miles farther north, while no human habitation lies between Kerguelen and the South Pole or would probably lie there if more islands lay between to furnish sites for settlements.

Now, taking these two contrasted stations as key points—Kerguelen as representative of oceanic conditions, and the corresponding point in Central Asia as representative of continental conditions—and following the parallels of 50° around the globe, we may gather a generalized view of the climatic effects of sea and of land, respectively, just above mid-latitude. Starting in Central Asia and following this parallel westward, we find that nearly half the great capitals of Europe lie north of it, viz: Moscow, Warsaw, Prague, Berlin, Stockholm, Christiania, Copenhagen, The Hague, Brussels, and London. Let it be granted without reserve that the western border of Europe is much affected by the warm currents of the Atlantic; but in consistency it must be equally noted and emphasized that this is *a special effect of a special part* of an ocean;

not its normal mean effect, and that there is *a similar special effect of the opposite kind* on the opposite side of the Atlantic. Such special effects largely offset one another in combining the enhanced warmth of the eastern sides of the Atlantic and Pacific oceans with the lower warmth of their western sides to get the mean for the whole parallel.

Following the 50° parallel onward across America, it is found to traverse the settled lands of Newfoundland, Quebec, Ontario, Manitoba, Saskatchewan, Alberta, and British Columbia, leaving the capitals of the first three and last on the south, and the capitals of the remaining three on the north. On the cold side of the Asiatic continent, the parallel traverses Sakhalin, the lower Amur region, Manchuria and Mongolia, to our starting point in Central Asia. Chita, Irkutsk, Tomsk, Omsk, Tobolsk, and other important cities, lie north of the parallel even in this eastern and colder part of the continent. From almost all points in this circuit of the globe human settlement extends 1,200 to 1,500 miles north of the 50° parallel, while the highest northern permanent settlement lies nearly 2,000 miles north of it.

Returning now to Kerguelen, for a similar circuit of the globe in the oceanic hemisphere, the first and almost only land traversed is southern Patagonia, a region of well-known inhospitality of climate and scantiness of population. The bleak little port of Puntas Arenas is almost the only town of note south of the 50th parallel in its entire circuit. The hard lot of the Tierra del Fuegans has become proverbial. The Falkland Islands lie only 1° to 3° south of the 50th parallel, and yet they show no signs of *aboriginal* inhabitants. Sea products and sheep raising have drawn to them about 2,000 Europeans and South Americans. The small islands of Auckland, Campbell, Macquarie, and Emerald, south of New Zealand near 60° S. Lat., seem to show some special effects of the warm return current of the South Pacific, but still they have rather severe climates and are only inhabited by a few sheep raisers. Taking the southern oceanic circuit as a whole, its climate is strikingly more severe than that of the northern more largely continental circuit.

Comparison of the oceanic and terrestrial 60° belts.—Advancing 10° poleward, it is to be noted that the parallel of 60° S. Lat. is practically oceanic throughout; it crosses no appreciable land. It traverses the southern portions of the Atlantic, Pacific, and Indian oceans and these portions have broad connections with the corresponding tropical portions, affording free facilities for a normal distribution of oceanic influence. Notwithstanding this, the belt is one of prevailing ice floes. The mean temperature at the surface is practically 0° C., and the climate very severe. Such life as appears at and above the surface seems to be chiefly that which lives directly or indirectly on the minute life brought to the region by *under currents* of the ocean. Such life is not therefore a direct index of the local climate. *There are no permanent human settlements on any island in this belt or on any lands within it.*

Quite in contrast to this oceanic parallel, the parallel of 60° N. Lat. lies chiefly on land. It however crosses the Atlantic, where narrowed at the north, touching the very apex of Greenland; it also crosses Behring Sea, a dependency of the North Pacific. It is inhabited by man in practically all its sections. It shows rather markedly the local effects of the warm currents of the ocean in raising the temperature on the east sides of the water bodies and of the cold currents in lowering it on the west sides. But even in Siberia, where the oceanic influence is unfavorable or remote, Vivninkskoe, Ust Maiskaya, Olekminsk, and Repolovskoe lie on or near the 60th parallel, while many settlements lie farther north. Following the parallel westward from Siberia, we reach Petrograd before much effect of the warm Atlantic currents is felt. Farther on, Helsingfors and all the settlements of Finland lie north of this parallel, while Upsala lies just south of it and much the larger part of Sweden lies north of it. Christiania is almost on the 60th parallel, while nearly all Norway lies north of it. The Scandinavian peninsula shows markedly the effects, not of "the ocean" in an unqualified sense, but of *the warm currents of the east side of the ocean.* This effect is offset, on the west side, by the Labrador Current, which gives rise to corresponding depressive effects. These latter are just as much effects of "the ocean" as are those of the Gulf Stream.

Even on the Labrador coast, Sangmijok lies just north of 60°, while in the interior numerous native villages and traders' stations lie near and north of this parallel. On the western coast of the American continent, which again is affected by *warm* ocean currents from the Pacific, there are busy towns and active human industries on or north of this parallel, such as Seward, Cordova, Valdez, and not a few others.

Thus the climate of 60° N. Lat.—equating the favorable and unfavorable effects of particular ocean currents—is very markedly more hospitable than that of the oceanic parallel of 60° S. Lat.

Comparison of the climates at the Arctic and Antarctic Circles.—The Antarctic Circle fits the Antarctic land much as a hoop fits a barrel. If the simple fact that a broad sea surrounding a relatively small land were sufficient to induce figs and magnolias to grow within the polar circles, it would seem that the sea-girt coasts of Antarctica should furnish an illustration, all the more so because the encompassing seas have broad connections with the tropical tracts of the Pacific, Indian, and Atlantic oceans. As a matter of fact, the climate of this sea-girt coast is extremely severe, as is too well known to require any special statement.

The Arctic Circle, on the other hand, lies on the ring of land which surrounds—with some interruptions—the Arctic Ocean, or, more truly, the North Polar Sea. It traverses land nearly all the way round, and great continents lie to the south, while an ice-covered sea lies within it. Scarcely 15 per cent of the Circle is occupied by arms of the sea. And yet, in contrast with the inhospitality of the Antarctic region, human settlements, and the lower life necessary to support these, are located in practically every segment of the Circle. Even in Siberia, where the conditions are most continental and where the adjacent seas are of the specially cold order, Sredne Kolymsk, Verkhoynsk, Krasnoe, Zashiversk, Shigansk, and Obdorsk lie on or near the Circle and not a few other settlements lie still farther north. Not a little of Siberia even at this high latitude is covered with coniferous forests.

Following the Circle on into Europe, we find lying on or near it, Kemitrask, Rovoniemi, Turtola, and Silbojock. It is of some special significance that near Vuollerim the Arctic Circle *is crossed*

by a railroad, while settlements extend nearly 300 miles farther north. In this region, however, the *warm* currents of the Atlantic have very considerable special effects. Iceland, the home of a creditable civilization, lies only a little south of the Circle in the midst of the narrowed portion of the Atlantic. The climate of east Greenland is notably depressed by an ice-bearing ocean stream that hugs the eastern coast, but on the western side, facing Davis Strait, the Arctic Circle cuts across the Danish colony, passing between the two capitals, Godhaab and Godhavn. This region, which has special interest from the climatic point of view, will be discussed more at length in a later article. In crossing North America, coniferous forests, native settlements, and traders' stations are encountered. The western coast is reached between the settlements Kalzebue and Kawalik, not far north of Nome.

Taking this whole land circuit together, it appears that after balancing the effects of warm currents against those of cold currents, the climatic picture stands in distinct contrast to that of the sea-girt coast of Antarctica.

Within the Polar Circles.—Within the Antarctic Circle nothing but severity and inhospitality of climate prevails. Such large living animals as inhabit the region live almost exclusively on sea-food brought to the Antarctic coasts by undercurrents of the sea and take on forms peculiarly adapted to this subsistence on imported food and to the severity of the climate.

The climatic import here, however, is confused by complications, and must be taken with some reserve on account of this. The area within the Antarctic Circle is chiefly land, while the area without is sea. The area within is not only land, but exceptionally elevated land, on the average, so far as known, and this elevation introduces a special factor which may be as important or even more important than either sea or land independent of elevation.

Within the Arctic Circle, the conditions are also peculiar in that a *frozen* sea occupies the center, surrounded by a ring of land broken by sea gaps. A frozen sea in such high latitude is almost constantly covered by snow, as is the land part of the season. A normal comparison of water surface with land surface is scarcely possible. Within the North Polar Circle, however, there is indige-

nous life developed into rather ample chains of dependent life, some of the chains being based on land plants, and some on sea plants, the former rising to the grades of hares, ptarmigan, reindeer, and the foxes and other animals that prey on these, while the latter rise into the much more complex and ample chains of sea life, ranging up to walruses, whales and Eskimos. These are pretty well scattered around the Circle but on the west side of Greenland in a land-girt region there are two limited areas of exceptional mildness of climate and remarkable abundance of life, constituting veritable climatic oases in the frigid desert of the north. These have a very significant story to tell which will be taken up in a later article.

Let us inquire whether theoretical considerations tally with the array of facts brought out by the foregoing comparisons.

THEORETICAL CONSIDERATIONS

To secure brevity, these may be put in the form of affirmative propositions.

1. *Water surfaces reflect more insolation than land surfaces.*—The surface of water is normally smooth and close-grained, so that it has much the effect of a polished surface and is highly reflective. In the high latitudes the angle of incidence of the solar rays is always low and for the larger part very low, and this gives a high percentage of total reflection from the water surfaces. The surface of the land, on the other hand, is rough and granular, so that it is highly absorptive; it closely approaches the theoretical "black body." The vegetal clothing of the land is also rather highly absorptive, due to a selective adaptation to meet the absorptive requirements of vegetal life. The combined effect is to render the land surface much more highly absorbant of solar rays than the sea surface.

2. *Water surfaces lose more heat by evaporation than land surfaces.*—The annual evaporation from sea surfaces is greater than that from the land surface, even though it is a few degrees lower in mean temperature. As a result less of the heat absorbed by the land takes the latent form and ceases thereby to have a heating effect. These differences are qualified, however, both pro and con, by the formation of surfaces of ice and snow on both land and sea. These surfaces are highly reflective and only slightly evaporative.

3. *The heat energy rendered latent by evaporation is carried across the climatic zone in a relatively ineffective form.*—Climate in the common sense of the term relates to the horizon occupied by living things. For convenience in this discussion we may regard the climatic zone as that between the earth's surface and the clouds. The heat energy rendered latent by evaporation crosses this zone embodied in vapor in a non-heating form. It only returns to a heating form when the vapor is condensed into cloud. When condensed into cloud, about half of the heat that returns to the sensible form is radiated outward and is lost; about half is radiated toward the earth and helps to compensate for its previous inertness. But the cloud itself interposes a highly reflective screen between the sun and the earth; a large percentage of the insolation is thus turned back to the sky without passing through the climatic zone or reaching the earth's surface at all.

There is some compensation, however. The vapor in rising from the surface across the climatic zone is a good absorber and re-radiator, especially of the "dark" rays from the earth. Over the sea this is only brought to bear on the lesser radiation sent forth from the cooler sea surface. On the other hand, the heat sent back from the land crosses the climatic zone more largely in the sensible form and is more largely absorbed in the passage and is repeatedly re-radiated.

While these considerations are not exhaustive, they sufficiently show that *a water surface in high latitude is a cooling agency.*

There is a simple mechanical consideration that deserves passing notice also:

4. *An increase of sea-room in which the warm equatorial currents may spread and cool themselves in intermediate latitudes, reduces their effectiveness in high latitudes.*—The effectiveness of the oceanic waters in conveying warmth to the polar regions is obviously dependent on the conservation of the heat received in low latitudes, during its long passage to the high latitudes. The more these warmed waters are spread out in their passage from the low to the high latitudes, the earlier will their heat be dissipated and the feebler their effects in the very high latitudes. It is quite clear that if the continents did not concentrate the tropical waters of the Atlantic

into the Florida Current (Gulf Stream) and similarly the tropical waters of the Pacific into the Japan Current, and by so doing restrain their spreading in their journey to the north, they would fail to raise the temperature of any given area in high latitudes as effectively as they do now. On the other hand, if the warm waters from the low latitudes are concentrated into deep streams by convergent lands, or better still if they are forced to flow poleward as deep currents protected from surface agitation by winds and from the radiation enhanced by these winds, they will be more effective carriers of heat to the high latitudes.

While some other theoretical considerations might be added, the foregoing confirm the inductions drawn from the preceding comparisons and give them great cogency. Observation and theory together make a clear and decisive case. The conclusion may therefore be drawn with great firmness that *extension of sea in high latitudes, in itself considered, normally renders the climate cooler than it would be if no extension took place.* It is to be scrupulously noted that this conclusion applies simply to the alternative of sea and land, not to special influences super-added on either side, such as warm currents, on the one side, or cold currents and great elevations of land surface, on the other. These super-added features are of course to be dealt with on their own account as special influences arising from super-imposed causes.

While the evidence is thus decisive against the assumed warming effects of sea extension in itself, a study of the evidence makes it clear that the ocean is a very effective climatic agency *both* in *raising* and in *lowering* regional temperatures in response to co-operating conditions.

This influential action has two phases that are to be distinguished in the study of geologic climates: (1) transient effects, and (2) secular effects. It is obvious that the superficial effects of the ocean are transient because the resulting temperature of the air is soon changed by radiation and the moisture supplied to the air is soon precipitated. If an effect is to be perpetuated by these means there must be a constant *renewal* of the activity. On the other hand, a prolonged effect may be produced by the great capacity of the ocean to store and retain heat, and this stored heat may be trans-

ferred from one latitude to another by the slow creep of the deeper waters of the ocean. This high capacity for heat storage and for slow transfer calls for serious consideration in the study of secular changes of climate. Its high value makes the ocean an important factor in the explanation of geologic climates; but only a factor.

THE GREAT HEAT-STORAGE CAPACITY OF THE OCEAN

(1) As is well known, the specific heat of water is roundly about five times that of average rock-substance. (2) The area of the deep ocean—neglecting the shallow waters of the continental shelf—is roundly twice that of the continental areas. (3) If we allow that the secular heating and cooling of the land areas—say such as takes place in changing to and from a glacial period—reaches 1,200 or 1,300 feet deeper under the land than under the sea before it is counteracted by internal heat (which seems, from such data as we have, an over-generous allowance), the depth subject to secular change of temperature under the ocean surface is roundly ten times that under the land surface by reason of the mobility of the water. Combining these, the thermal potency for secular thermal effects is $5 \times 2 \times 10$ in favor of the ocean considered as a climatic influence. This great secular potency is to be combined with the much more transient potency of surficial action in reaching the total influence and the combination will sometimes be additative and sometimes subtractive.

In this article the choicest bit of evidence that simple sea extension is not a controlling factor has been passed over with little more than mention, and left for consideration in another article, because, in the first place, it was not necessary for the support of the main proposition and, in the second place, because it forms an admirable introduction to the consideration of the storage capacity and carrying power of the ocean. Starting with the existing status, it forms, a first step in the study of the secular effects of the ocean on climate. It prepares the way for passing from the present long-time, long-distance action of the ocean to the greater effects of like kind that obtained at intervals during the geologic ages.

THE RED BEDS OF THE FRONT RANGE IN COLORADO: A STUDY IN SEDIMENTATION

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Aim of this article.—The term "Red Beds," as used in this article, needs some definition. The term includes only those Colorado formations known as the Fountain, Lyons, and Lykins series and their accepted time-equivalents east of the Continental Divide. These beds lie unconformably on pre-Cambrian granites and gneisses,[1] occur more or less continuously from Wyoming to New Mexico, and have an undetermined extension eastward from about longitude 105° W. They are tilted, often to angles of over 60°, the direction of dip being southeast to east. The present paper is not concerned with their age, already established by Henderson,[2] the Fountain and the Lyons as Pennsylvanian, the Lykins as Permo-Carboniferous in its lower part, Triassic (?) in its upper part. Rather, the paper aims to contribute to the literature of sedimentation by (*a*) fully describing the beds and (*b*) discussing both the conditions under which the sediments were laid down and the paleogeography at such times. Though the writer is familiar with the "Red Beds" of the Black Hills, of the Bighorn uplift, of the Laramie region, and of southeastern Colorado, the conclusions are based chiefly on a two years' study of the stratigraphy from the Cache la Poudre River, about 16 miles south of the Wyoming line, to Canyon City, west of Pueblo.

THE FOUNTAIN FORMATION

Description.—It is difficult to give a typical section for the Fountain formation because of its great lateral and vertical varia-

[1] At Canyon City the beds lie unconformably on Mississippian limestone and overlap on Ordovician limestone.

[2] J. Henderson, "The Foothills Formations of North-Central Colorado," *Colo. Geol. Surv., Bull. 19* (1920). Earlier discussions are chiefly by N. M. Fenneman, "Geology of the Boulder District," *U.S. Geol. Surv., Bull. 265* (1905), and R. M. Butters, "Permian or Permo-Carboniferous," *Colo. Geol. Surv., Bull. 5* (1913).

tion. Yet the following section, made 500 feet north of Gregory Canyon, west of Boulder, fairly represents the beds in the strip from Cache la Poudre River to Canyon City.

Lyons Sandstone, Conformable (?) upon	Feet
u Arkose to conglomerate, massive, reddish, cross-bedded (torrential); pebbles qz. and orth., the former subangular to well rounded, and up to 3 in. in diameter, the latter chiefly angular cleavage fragments; also granite and pegmatite pebbles, and muscovite flakes $\frac{3}{8}$ in. long; iron stained, slightly calcareous arkosic matrix; breakage across pebbles	35
t Sandstone, chiefly massive, traces of $\frac{1}{4}$-in. to 2-in. beds; red, with areas leached to gray and with greenish perfectly rounded $\frac{1}{2}$-in. fragments of arkose apart from leached areas; hard, fine-grained, slightly calcareous, ferruginous (ferric iron); breaks to angular blocks and varies laterally to arkose	10
s Arkose, massive, dark, pink, coarse—much as in bed *u*	10
r Sandstone to arkose, red to whitish—much as in beds *t* and *u*	2
q Sandstone, massive, red; fine grained, dense, firmly cemented (see also bed *t*)	3
p Mainly covered; near top, various massive coarse arkose beds, cross-bedded; at about middle a massive 8-ft. arkose, with what may be laminations of varying coarseness; lower part much as upper, pebbles averaging 1 in. in diameter, not firmly cemented in an arkosic matrix	200
o Partly covered; arkose in 3-ft. to 5-ft. beds, reddish or leached (?) to gray; fairly even-grained, subhard, grains averaging less than $\frac{1}{8}$ in., but with pebbles up to 2 in.; arkose much as above, with thin beds of reddish shale, highly muscovitic, and thin beds of red sandstone, platy, muscovitic	92
n Partly covered; arkose much as in bed *u*; arkose as above, with sandstone and shale (see also bed *t*) ...	90
m Conglomerate, arkosic, massive, reddish—much as in bed *u*, with 2-ft. lenses of well-rounded, coarse gravel, containing granite and white qz. pebbles up to 3 in. in diameter	30
l Sandstone, deep red to purple, seemingly massive but leached in streaks possibly parallel to obliterated bedding-planes (see also bed *t*)	5
k Conglomerate, much as in bed *m*, torrentially cross-bedded	60
j Shale (?), thinly and unevenly bedded, dark red; very arenaceous, with flakes of muscovite	3
i Shale (?) as above, but evenly laminated	3
h Sandstone, massive, dark red; fine grained, with muscovite flakes	5
g Sandstone, massive but seemingly thin bedded ($\frac{1}{2}$ in. to 8 in. thick); see also bed *t*	7

f	Shale (?), thin bedded, reddish, arenaceous, muscovitic	2
	(biotite dacite porphyry sill)	25
e	Covered	50
d	Sandstone, much as in bed *t;* greenish arkose balls from lower beds, or else representing coarse sands long rolled about	10
c	Conglomerate, matrix arkosic, pebbles up to 8 in. in diameter, qz. and orth. preponderant, but much granite fine and coarse grained, of both biotite and hornblende facies; also rarer large limestone fragments, hard, crystalline, reddish; in nature much as bed *u*	75
b	Conglomerate, much as in bed *c*, but with lowest beds merely gritty to arkosic, and with many lenses of pebbles up to ½ in. in diameter	25
a	Shale (?) finely laminated, dark red; subhard, very arenaceous and ferruginous, somewhat calcareous	1
		718

(Unconformable on Granite)

Analysis of this section does not of course reveal the lateral variation in size of grain, a significant characteristic of the formation; beds wedge out and coarse grain gives way to fine, often in a few feet. It should further be mentioned that north of the Cache la Poudre River appear intercalated limestones, carrying marine fossils and becoming of increasing importance as the Wyoming line is approached. At Colorado Springs, also, some of the sandstone beds are grayish to greenish, and, 475 feet up in a 2,000-foot section, a marine fossil, *Lingulodiscina*, is found in a pocket of green shale.

Analysis does however disclose other salient characteristics of the Fountain formation, *all* which must be explained and harmonized in an interpretation of the sediments. The main characteristics are (1) absence, anywhere in the sequence, of the marine rhythm, conglomerate to sandstone to shale, or vice versa; (2) a consequent great thickness of unassorted, unsized conglomerate and arkose, with only occasional fine-grained arenaceous material; (3) a predominance of subangular and angular pebbles, often of bowlder size, and notable among which are muscovite flakes ¾ inch long,[1] fresh feldspar fragments, and bits of limestone; (4) freshness of the feldspar; (5) a peculiar type of cross-bedding, described below.

[1] N. M. Fenneman, *op. cit.*, p. 22, assumes that the muscovite is secondary. S. F. Emmons, *U.S. Geol. Surv., Monograph 12*, p. 68, had long before recognized it, under the microscope, as primary in large part.

Less significant, perhaps, are the red color, the presence of calcareous as well as hematitic and siliceous cement, and (except as above noted) the absence of fossils.

The cross-bedding is scarcely of a type recognized by the textbooks. The scale is medium, the cross-bedded horizons seldom occupying more than 2 feet vertically. In general, the dips are at low angles, though by no means always so, and run in all directions, both parallel to the dip of the true bedding, at right angles to it, and obliquely. The cross-bedded layers are truncated both by horizontal beds, as in "torrential" cross-bedding, and by other and highly irregular cross-beddings.

The thickness of the formation also has a bearing on its interpretation. At the Cache la Poudre, the thickness is 600–725 feet. Thence southward, the thickness is 900–1,075 feet west of Fort Collins; 1,000 feet at Lyons; 800–1,500 feet near Boulder; 500 feet at Morrison; 4,500 feet, at the maximum (the average being 2,000 feet), at Colorado Springs; 1,000 feet at Canyon City; 250 feet a mile south of the Arkansas River; 200 feet at a point 6 miles northwest of Badito. If Fountain beds are present in the Purgatoire Valley southwest of La Junta, recent well borings would indicate there a thickness of about 1,000 feet.

Interpretation of conditions of origin: the marine hypothesis.—As far as the writer knows, discussions of the origin of the Fountain sediments make them marine. The most complete interpretation is that of Fenneman (1905), accepted by Butters and George (1913) and by Henderson (1908)—though the latter (personal communication) is now in accord with the present writer. Fenneman's view, briefly, is this. In late Pennsylvanian time, a north-south shore line, of unstated length, existed 10 to 12 miles west of the present foothills of the Front Range. This land was of granite and of very low relief,[1] though, as Fenneman deduced from the absence in the Fountain sediments of "residual soil" material, the land was not a peneplain in the usual sense. On this "featureless" land, the sea encroached, its advance and resultant planation of the shore keep-

[1] N. H. Darton, *U.S. Geol. Surv. Prof. Paper 52*, p. 16, differs from Fenneman at this point, by emphasizing relief. Relief is certainly conspicuous on the "old plain," as now visible near Red Mountain, close to the Wyoming line.

ing pace with the disintegration of the granite under semiarid climatic conditions. The rock fragments were so rapidly buried in a constantly subsiding trough that they were little rounded or comminuted. Violent currents in the shallow sea produced the cross-bedding.[1]

Interpretation: the writer's river hypothesis.—Behind the marine hypothesis is the weight of tradition. Yet the hypothesis seems to have serious defects. Scarcely one characteristic of the beds suggests to a modern sedimentationist marine conditions; taken together, the characteristics almost irresistibly point to a continental origin. The lack of a marine rhythm; the thickness of the conglomerate or arkose; the lateral variation; the unsorted, unsized, angular material; the red color; the freshness of the feldspar; the type of cross-bedding—this combination emphatically indicates deposition by a river in a semiarid climate. The presence of *Lingulodiscina* at Colorado Springs can be harmonized with such a point of view.

Nor is such a point of view entirely a matter of theory. It has been checked by studies both of the Pliocene Nussbaum formation of eastern Colorado, admittedly of river origin, and of the sediments now being left in alluvial fans and on flood plains by Boulder, Clear, Big Thompson, Fountain, and other "creeks" debouching from the Front Range. The correspondence, except for color (a matter easily explained), is well-nigh perfect. Photographs were taken of Fountain sediments newly revealed in cuts at Golden and of modern flood beds exposed at Boulder in diggings. Pennsylvanian and modern sediments can scarcely be distinguished from each other.

By these studies, the origin of the cross-bedding in the Fountain, e.g., becomes manifest. In flood time, if not restrained by man, the present "creeks" would wander far from their channels, trespassing on each other's territory and confusing coarse and fine sediments. In fact, the Nussbaum "creeks" did so wander. The result, as

[1] N. M. Fenneman, *op. cit.*, pp. 54–57. Occasionally the suggestion is still met that the entire present Rocky Mountain area was submerged, the Fountain thus being an eastward extension of West Slope formations like the Maroon conglomerate. But the Maroon conglomerate is *finer* than the Fountain material, and surely such large bowlders as are common in the Fountain could not have been transported far.

evidenced in miniature floods, is the production of much "scour and fill" cross-bedding, which is of medium scale and parallel to the dip of the true bedding, as in the Fountain sediments. In addition, as the flood subsides, there arise little islands, separated by unorientated rivulets. The dip of deposits on these islands and temporary "shores" is at all angles and in all directions, even contracurrent, again as in the Fountain sediments.

Interpretation: climate and paleogeography.—Can the type of river sedimentation be further determined? It is believed that it can—by consideration of climatic and paleogeographic possibilities such as should not be ignored in modern studies. Almost certainly the climate can be set down as semiarid, with all that that implies. As to paleogeography, the marine hypothesis assumes, as has been said, that directly to the west of a shallow sea-trough lay land of unknown extent. The writer also thinks that the ancient Colorado rivers must have flowed from either the west, northwest, or southwest. The basis of belief is not the time-worn statement that the sediments are those which would have been derived from a granitic mass similar to that west of the present-day foothills. That argument is not convincing. But, if the sediments came from north of Colorado or east, they should have been coarser in those directions. To the east, Fountain material seems entirely lacking.[1] To the north, the presence of the intercalated limestones carrying marine fossils reveals a sea, strait, or bay in that direction.[2]

It is then quite possible that streams flowing almost east from a Paleozoic Front Range furnished the Fountain material; if so, the Fountain is an ancient Piedmont plain, with here and there alluvial fans higher than elsewhere, and with masses of sheet wash. The nature of the sediments fits in with this idea. Furthermore, since the Maroon conglomerate and other West Slope series seem

[1] In western Kansas, the Cimarron shale, 1,000 feet thick, lies unconformably on granite, but it would seem to correspond to Lykins material in Colorado. In any event, it is far finer grained than the Fountain; the same is true of what may be 1,000 feet of Fountain sediment in the Purgatoire Canyon south of La Junta (maximum size of pebbles 2 inches). See also N. H. Darton, on the Cimarron shale (Syracuse-Lakin folio, p. 2).

[2] The writer believes, because of studies made in Wyoming, that a strait connecting with a western sea lay between Colorado and a Wyoming land mass.

to be of much the same age as the Fountain formation, a late Paleozoic Front Range axis must have been continually rising in order to supply such a thickness of sediments. The induction is not out of accord with the present-day belief that the land mass of "Columbia" underwent marked elevation in late Mississippian time, nor with the view of Spurr[1] and others that rejuvenation of Colorado land masses occurred in early Pennsylvanian time.

It is here desired, however, to suggest another possibility—though by no means to cling to it. The thickness of the Fountain formation increases, in general, from Cache la Poudre River to Colorado Springs and then again decreases. It will also be recalled that in the Colorado Springs section *Lingulodiscina* occurs 475 feet above the base. Once, at least, there must have been an embayment here. It may be that, although the main axis of the late Paleozoic Front Range ran north-south, east-west spurs occurred north and south of Colorado Springs, these spurs acting as divides to rivers flowing northeast and southeast over whatever foreland stretched in their courses. Limestone pebbles in the Fountain near Boulder could not now be derived from the immediate west, and at Badito are found the largest bowlders (much larger than those at Colorado Springs) in the Fountain sediments. Only further and very detailed studies[2] can throw more light on the paleogeography of Fountain times, but at least such evidence as is attainable strengthens the river hypothesis.

THE LYONS FORMATION

Description: typical Lyons.—The typical Lyons sediments, though having the same strike and dip as the Fountain beds, have not quite the same distribution, and are not easily recognized

[1] J. E. Spurr, "Geology of the Aspen Mining Region," *U.S. Geol. Surv. Monograph 31*, p. 32.

[2] The Glen Eyrie shale, found only at Colorado Springs, needs closer attention. G. I. Finlay, "The Glen Eyrie Formation," *Jour. of Geol.*, Vol. XV (1907), p. 589, suggests that the Glen Eyrie shale lies unconformably beneath the "purplish-red sandstone," with "intercalated gray or light-pink arkose" with which the Fountain begins. The Glen Eyrie shale, however, is also of Pennsylvanian age, and its *Lepidodendron* flora implies swampy lowlands. The facts strengthen the suggestion that the Colorado Springs region at first marked an axis of depression rather than of elevation.

save from the Cache la Poudre River to Colorado Springs, but in this strip they are so homogeneous that a vertical section is unnecessary. Their contact with the Fountain is sharply defined, since they consist essentially of fine-grained red or pink to white sandstone, at times cemented to an orthoquartzite—a process still continuing. Under the microscope, the grains, except for a little comminuted feldspar and muscovite, are seen to be quartz, are notably rounded and uniform, and in diameter vary from 0.1 mm., or less, to 1 mm. The color is due to films of ferric oxide coating the grains. The thickness of the formation ranges from 850 feet at Colorado Springs to a few hundred feet north of Lyons. Other major characteristics important for interpretation are the type of bedding (including cross-bedding) and the occurrence of ripple marks and (rarely) of amphibian tracks. Of minor significance are beautiful dendritic markings due to manganese oxide and small, rounded cavities, marking spots where limonitic concretions have fallen out. Locally, as at Colorado Springs, a heavy conglomerate, with *rounded* bowlders 2 feet in diameter, occurs near the middle of the formation.

The significance of the true bedding is not that it is, to the casual glance, massive, or, when more carefully examined, either thinly platy or slabby, hence good for flagstones, but rather the fact that close scrutiny reveals that all the beds consist of laminae from $\frac{1}{64}$ inch to $\frac{1}{8}$ inch in thickness. These commonly alternate in light and dark bands (disguised by the general pink of the formation), the bands being minutely cross-bedded in uncertain patterns. Much more prominent is cross-bedding on such a scale that its interpretation always attracts comment. The true bedding now dips eastward at very steep angles, and in places between a 10- to 15-foot thickness of such slabs will appear an equal thickness of cross-bedding, abruptly truncated above and below, and *dipping eastward at an angle always less than that of the true bedding.* Nor is this all. Less conspicuous, but seldom lacking, is another set of large-scale cross-beds *dipping at present steeply westward.* A moment's reflection will show that, if the original dip of the beds were restored as a gentle eastward slope, the cross-bedding which now dips eastward would dip gently westward and that which now dips

westward would dip eastward—though at a higher angle than that of the true bedding.

Description: variants of the Lyons formation.—As has been suggested, south of Colorado Springs and north of the Cache la Poudre River, the Lyons beds are not easily recognizable. The southern region may be disposed of briefly. Lateral tracing of the Lyons beyond Colorado Springs is impossible, and certain "coarse deep-red sandstones,"[1] overlying the Fountain sediments west of Pueblo, and "containing a considerable mixture of clay"[2] may be either of Lyons or Lykins time. The same is true of 100 feet of a brick-red sandstone north of Badito; of 30 feet of a massive pinkish-gray sandstone on Grape Creek in the Royal Gorge region; and of certain brick-red material in the Purgatoire Canyon.

The area north of the Cache la Poudre River has been most closely examined by Butters and George; issue is taken with their view with caution, though in this divergence Henderson is again in accord with the writer. Butters' view of this region is as follows. Overlying the typical Fountain material (with its intercalated limestones), he finds a thin series of sandstones and limestones, which he believes to represent a distinct *time-unit* and which he calls "Ingleside"; the deposition of this material transpired, he thinks, between the end of Fountain time and the time of deposition of higher beds supposed to merge southward into material like that of the Lyons.

The writer investigated this region under unfavorable conditions. He is inclined however to follow Henderson in denying validity to the term, "Ingleside," and in considering that, to the south, the lowermost "Ingleside" merges into topmost Fountain and the highest "Ingleside" into lowermost Lyons. The bearing of the discussion on a possible unconformity between Fountain and Lyons is manifest.

Interpretation: the marine hypothesis.—The traditional explanation of the Lyons formation is that it, like the Fountain material, is marine. Fenneman supposes that an eastern sea still encroached upon the land and that waves and currents rolled about the latest

[1] C. E. Gilbert, The Pueblo folio (unpaged).

[2] R. M. Butters, *op. cit.*, p. 75.

Fountain sediments until the orthoclase was decomposed, the muscovite comminuted, and the quartz both comminuted and rounded to a marked degree. The puzzling cross-bedding which now dips eastward at a gentler angle than that of the true bedding he explains more particularly. At certain points of the coast line, he argues, notably at Boulder and Golden, there were elevated east-west arches, separated by bays. Across these bays longshore currents built bars. The cross-bedding represents the originally shoreward dip of this sand-bar.[1]

Interpretation: the writer's desert hypothesis.—Aside from the fact that the marine hypothesis ignores that other large-scale type of cross-bedding which the writer has described, that which under approximate original conditions would dip eastward at a higher angle than the true bedding, many difficulties confront Fenneman's viewpoint. Why do the Lyons sands contain no *coarse* material from the assumed arches? How many bars were there, inasmuch as the cross-bedding is not limited to the Boulder and Golden localities? Are the regular laminae, of which all the beds ultimately consist, consonant with a hypothesis which requires violent waves and currents to comminute and round the quartz grains? Above all, if the trough continued to subside, how could quartz grains, the largest less than 1 mm. in diameter, come to lie in such sharp contact with coarse arkose? And why, if the grains were rolled about under water, did they acquire such films of ferric oxide that the whole formation looks pink to red? Or is the Lyons color entirely secondary?

A very different hypothesis—that the climate grew more arid, that the rivers of Fountain time shrank to nothingness, in short, that desert conditions prevailed when the Lyons sediments were laid down—may not solve all of the difficulties, but it is here advanced as more plausible than the marine hypothesis.

There is certainly no evidence of uplift of the western land at the close of Fountain time. It would accordingly have been lowered by erosion, the rivers would have headed farther back, and they would have brought less and finer materials to the forelands. Winds would thus have had an opportunity to whip about the diminished

[1] N. M. Fenneman, *op. cit.*, pp. 58–60.

Fountain sediments, grinding the feldspar and muscovite to minute fragments and rounding the quartz grains to their unusual uniformity of size and sphericity. Since there would have been a limit to the depth of such wind work, though none to the amount of comminution, the sharp contact of Fountain and Lyons is accounted for reasonably. The very fine irregular cross-bedding on the laminae is such as may be observed on fine, modern sand layers. The large-scale cross-bedding, dipping in two opposite directions at gentle angles, may well have been that of sand dunes, whose topmost layers are truncated as the winds change direction. The uppermost sands, too, are whitest, as if protracted whipping about had removed some of the ferric oxide film. The local conglomerates may have been due to rare, vehement floods from the distant highlands; the boulders are *rounded*, as if they had moved far. Even the sporadic amphibian tracks and the occasional obscure ripple marks are consistent enough with the hypothesis.[1]

There would seem to be, then, a kind of unconformity between the Fountain and Lyons sediments—an unconformity, curiously enough, for which Butters' view of the "Ingleside" would call. But the unconformity would be of an unnamed type, for the record of what happened is not lost. The record takes the form of a geologic palimpsest, as it were—Lyons history being superscribed upon erased Fountain history.

Interpretation: climate and paleogeography.—Lyons climate has already been interpreted as dryer than that of Fountain time. As to relation of land and sea, all that can be predicated is that, as Pennsylvanian time continued, marine or semimarine conditions still prevailed to the north of Colorado, and probably to the east. Western highlands were lowered.

[1] C. E. Vail, "Lithologic Evidence of Climatic Pulsations," *Science*, Vol. XLVI (1917), pp. 91–93, has preceded the writer's point of view by simply stating that the Lyons is eolian, though he has not dealt with its larger problems. In fact, he confines himself to one interesting suggestion. That alternation of light and dark laminae which has been noted he views as the testimony to "climatic pulsations." The "white" laminae he describes as comprising "very well-rounded grains of white quartz, with scattered specks of iron oxide," and the "brown" laminae as being composed of "angular and subangular" grains, with coatings of iron oxide." The brown laminae are then explained as laid down by torrential rains on a desert, the white laminae as being purely eolian. The distinction between the grains of the laminae has perhaps been overemphasized.

THE LYKINS FORMATION

Description: typical Lykins.—The typical Lykins material is both very different from, and much more variable than that of, the Fountain or Lyons series. Yet, except in one important particular, the following section, made at Bear Creek, 3 miles south of Boulder, is representative of the strip from Lyons to some distance south of Colorado Springs.

Morrison Sandstone, Unconformable on	Feet
k Sandstone, slabby (2-in. to 4-in. beds), rich brown-red, weathering to red; fine-grained, subhard, ferruginous, somewhat calcareous, slightly argillaceous, breaks in little blocks; rare, comminuted muscovite fragments; ferruginous mud lumps and ripple marks (current type, setting north)	20
j Shale, fissile, red, sandy	10
i Sandstone, massive, especially the lower 10 ft.; brown, with green dots, splotches, and lenses, the latter up to 20 ft. long, and passing laterally into sandy shale, almost fissile; no ripple marks observed; mud lumps common. Otherwise, much as in bed *k*	30
h Shale, red, weathering red, thin bedded to fissile; splotched and lensed with green, varying laterally to shaly sandstone	10
g Sandstone, almost massive, red—much as in bed *i*, but no mud lumps	60
f Covered; undoubtedly sandstone and shale, as in beds *g* and *h*, the sandstone predominant, with delicate laminae ($\frac{1}{32}$ in.) on $\frac{1}{2}$-in. beds, the laminae finely cross-bedded	150
e Sandstone, known as "crinkled" and an important horizon-marker from at least west of Fort Collins to points south of Pueblo; very finely laminated in twisted, broken, and brecciated folds, the average thickness being $\frac{1}{16}$ in., colors alternating red and white; fine grained, hard to superhard, highly calcareous; blocky, shaly sands may be intercalated; upper 6 ft. here limestone, grayish, hard, arenaceous, somewhat brecciated, with calcite crystals in veins	18
d Sandstone, massive, weathers in blocky fragments, simulating $\frac{1}{8}$-in. to 1-in. beds; red, with less green splotches than in upper beds; variant to *k* type	40
c Sandstone, massive, red, hard	6
b Sandstone, much like *k*, but with few mud lumps or ripple marks; green splotches as in bed *d*	34
a Sandstone, massive, red, weathers in blocky fragments, much as in bed *d*	20
	390

As revealed in this section, the characteristics upon which the interpretation of the Lykins depends are (1) seeming conformity

with the Lyons; (2) fine and uniform grain; (3) vertical alternation of shale and sandstone and lateral passage of the one into the other; (4) presence amid the general red material of green splotches and lenses; (5) occurrence of mud lumps and ripple marks; (6) very fine cross-bedding; (7) origin of the "crinkled" bed, which is not always sandstone, but may carry some thin beds of limsetone, and which may involve varicolored shale lenses, or may even be limestone. Not disclosed in the section is the important fact that the upper few hundred feet of the Lykins often contain gypsum beds, a notable one being 90 feet thick at Red Creek, southwest of Colorado Springs. These gypsum beds all seem to lie above a horizon equivalent to that of certain limestones near the Wyoming line, which carry marine Permo-Carboniferous fossils.

Description: variants of the formation.—South and north of the Cache la Poudre to Colorado Springs strip, conditions are as follows. If the sandstones and shales lying above the Fountain sediments west of Pueblo and Walsenburg (see p. 200) are not of Lyons time, they are probably of Lykins time, since they are unconformable beneath Morrison beds. In the Purgatoire Valley, the Lykins, in all probability, is represented by 800 feet of red sandstones and shales, with gypsum. Any still further eastward extension of the Lykins is discussed under its paleogeography. As to northern Colorado, Butters and the writer (still in accordance with Henderson) are again at variance. Butters believes that the Lykins formation lies directly upon his "Ingleside," and that the writer's "Lyons" is a southern expansion of a thin cross-bedded sandstone which first appears near the Cache la Poudre River and rapidly thickens southward.[1] The writer thinks that Butters' lowest Lykins bed (a shale) merges laterally southward into lower Lyons sands, and that the cross-bedded sandstone, so emphasized by Butters, merges into somewhat higher Lyons sands. The variance hardly bears upon the problems here under discussion, because the northern beds are still marine or semimarine.

Interpretation: marine hypothesis.—Those who regard the Fountain and Lyons sediments as marine assume, without any argument, that in Lykins time the eastern sea deepened.

[1] R. M. Butters, *op. cit.*, p. 76.

Interpretation: the writer's upper-delta hypothesis.—If it is difficult to see why the hypothetically marine sands of the Lyons are pink to red, it is more difficult to picture deepening waters depositing yet redder sediments. It would be daring, indeed, to assume that the present red of these sands and shales was caused by later dehydration of originally gray-green sands; yet, if the western land was now in its last stages of degradation and furnishing primarily red material, why was not the red matter chiefly *mud?* Incidentally, could not invertebrates live in the deepening sea? Marine shale usually preserves traces of life, and, though shale is not predominant in the Lykins, it is nevertheless abundant.

Without directly objecting further to the marine hypothesis, is it not more plausible that in early Lykins time climatic conditions changed, so that the desert slowly became a flood plain or the upper reaches of a delta? There may have been elevation to the west, though the Lykins sediment is as fine grained as the Lyons; there may have been increased rainfall in that region; there may have been solar fluctuations; there may have been an advance of the eastern waters. In any event, the sediments, in many ways, resemble those of the upper stretches of a delta. Already in the lower beds mud lumps begin to appear, and whence arise mud lumps if not from river action? The green splotches and lenses, too, first appear in the lower Lykins. The coloring matter of these green blotches is revealed by analysis as ferrous iron. It would seem unlikely that green was once the prevailing color of sediments now so red. Far more likely it would seem that the blotches are probably due to the reduction of ferric iron, and the most natural reducing agent would be the carbonaceous matter found here and there on the supposed delta. Frequently characteristic of a delta, also, is the change of red sandstone into green shale within the space of a few feet horizontally. Amphibian tracks, too, have been found.

Occasionally, in the time required for the deposition of the Lykins, a sea might have advanced on a delta. Such may be the explanation of the "crinkled" bed, which always occurs near the base of the Lykins. If it were due to a north-south stress in Cretaceous time, as stated by Fenneman[1] and others, strata above and

[1] N. M. Fenneman, *op. cit.*, p. 26.

below might be expected to exhibit signs of disturbance. They do not. If the folding were due to change in volume in underlying beds, "crinkled" strata ought to be fairly common. The Lykins "crinkled" bed seems to stand almost alone. Without asserting that the final word has been said, it may be suggested that limy strata slipped, buckled, and brecciated upon a fairly steep sea slope at a date when the foreland of early Lykins time was submerged.

In upper Lykins time (Triassic ?),[1] on the other hand, the climatic pendulum was probably again swinging toward increased aridity, hence the well-known but sporadic and discontinuous deposits of gypsum, and the coarsening of the upper sandstones. Within the last year, also, borings have penetrated salt beds near Eads in southeastern Colorado.

Interpretation: climate and paleogeography.—Climate has been treated of, but it is interesting that what is known of Permo-Carboniferous paleogeography bears out the upper-delta hypothesis. Case, in an elaborate study of Permo-Carboniferous conditions, is rather emphatic in tracing the marine limestone (Wreford) of southern Kansas into the Red Beds (continental) of Oklahoma and thence north to Nebraska and the Black Hills. There would seem, also, to be a relationship between the Cimarron shales of Kansas and the Lykins through the gypsiferous beds at Two Buttes (25 miles west of the Kansas-Colorado line) and in the Purgatoire Valley (see p. 204). Case remarks, finally, that the lower Red Beds of Permo-Carboniferous age are in two areas of deposition, separated (see his Plate IV) by a continuous land mass extending from Mexico indefinitely northward, but at least uninterruptedly to far beyond Colorado.[2] The area of deposition involved in the present problem Case defines as reaching from "north-central Texas to the Black Hills and west to the Front Range of the Rocky Mountains."[3] All this area "can only be considered," he writes, as "great flood plains or deltas."[4]

[1] Whether or not the upper few hundred feet of the Lykins are Triassic, the writer is not prepared to discuss. The evidence consists of a Belodon bone found by Darton in the Purgatoire Valley. See also E. C. Case, "The Permo-Carboniferous Beds of North America," *Car. Inst. Pub. 207*, p. 66.

[2] E. C. Case, *op. cit.*, p. 88. [3] *Ibid.*, p. 71. [4] *Ibid.*, p. 91.

The presence of marine fossils in northern Colorado, up to within roughly the last hundred feet of the Lykins series, would indicate that the expresssion, "continuous land mass," is too sweeping. Case's evidence, however, as to deltaic conditions in Colorado accords with the writer's interpretation of the Lykins sediments.

Conclusions.—It may now be proper to summarize briefly the conclusions reached in this article. They are (1) that the Fountain formation of Colorado is very largely an alluvial fan or braided-river deposit; (2) that the Lyons formation of Colorado is chiefly eolian under desert conditions; (3) that the Lykins formation is chiefly an upper-delta deposit.

ISOSTASY AS A RESULT OF EARTH SHRINKAGE

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In spite of the apparently indisputable evidence that the earth's crust is in almost perfect isostatic adjustment, geologists have been slow to accept the theory of isostasy. The subject received wide interest at the 1921 meeting of the Geological Society of America. At this meeting it developed that the opposition to the theory was directed in part against the common interpretations of some geological phenomena made by the isostasists and also against the lack of interpretations of other geological phenomena which have a bearing on isostasy and appear to be inconsistent with it. Therefore the question arises as to the possibility of explaining these various phenomena in such a way as to satisfy both geological and isostatic requirements.

Those isostasists who claim that mountain ranges have been uplifted by the vertically acting forces of isostasy rather than by the horizontal forces produced by earth shrinkage, have still to explain much in regard to folding and thrust faulting. Bowie believes that these are due to the irregularity of the application of the vertical forces.[1] Irregularities of uplift might produce tilting of surfaces, block faulting, similar folding, and other phenomena which do not indicate a distinct shortening of the crust, but where the cross-section of a range shows that points on the sides of the range have actually moved toward the center so much that there has been shortening of 40 or 50 per cent of the original section, then not vertical forces, but horizontal forces must have been the cause of the structure. It is easy to duplicate experimentally the effects of lateral shortening and to reproduce on a small scale any type of fold found in nature, but it is dynamically impossible to produce overturned folds and thrust faults of large proportions by contrivances which apply

[1] W. Bowie, *Geol. Soc. of America*, Vol. XXXIII (1922), p. 280.

only vertical forces. Hayford's idea that undertow produces folding[1] meets with the same objection, that horizontal surface forces are necessary to produce the shortening which must accompany parallel folding. If it is these vertical forces that produce folding, why is it the peneplain uplifts, which are perhaps the most typical cases of vertical uplift, are generally not accompanied by pronounced folding?

Since there is good geological evidence for shortening of the earth's crust and good geodetic evidence for isostasy, it is fitting that we should examine the possibility that there is no antipathy between the two theories. It has been said that diastrophism due entirely to isostatic forces would soon run down, but if we can consider that earth shrinkage is a cause of perpetuation of the inequalities of the earth's surface, the difficulty is removed. It remains then to explain how the wrinkling of the crust and the various phenomena which geological history tells us have accompanied the changes of the earth's surface could have been produced without the loss of that isostatic adjustment which geodesy leads us to believe has been a basic condition. The following observations appear to be contradictory to the theory of isostasy.

First, the squeezing in of material from the sides in the change from geosynclines to mountain ranges makes it seem likely that the mountain ranges would be a greater burden on the crust than the geosynclines.

Second, the elevation of plateaus from low lying plains appears to suggest that during the process there were important changes in the weighting of the crust with reference to the level of isostatic adjustment.

Thirdly, the development of peneplains and their subsequent uplift gives the impression that the crust is strong enough to resist for long periods without yielding to the forces of isostatic equilibrium.

If diastrophism has been periodic, this also might indicate that the crust was strong enough to withstand great burdens before yielding.

[1] J. F. Hayford, *Science*, New Series, Vol. XIII (1911), pp. 199–208.

MOUNTAIN GROWTH WITHOUT LOSS OF ISOSTATIC ADJUSTMENT

In regard to the possibility of change from geosynclines to mountain ranges without altering the isostatic equilibrium, Bowie offers an explanation which disregards lateral shortening.[1] The gist of this is that while the geosynclines are subsiding, the isogeotherms are depressed beneath them. When subsidence ceases these isogeotherms rise to their former position. The resulting heating of the mass is supposed to be the cause of the mountain uplift by heat expansion. It seems rather doubtful that the slow sinking of a geosyncline would cause a depression of the isogeotherms, but granted that this would actually occur, it must be remembered that subsidence of such geosynclines as the Appalachian was often interrupted and for long epochs the geosyncline was not covered by the sea. If we accept Bowie's idea, we have to account for the lack of mountain building during each of these intervals. The idea therefore does not agree with accurate geological observations.

Considering mountain building as the product of compressive forces, Wood has made the important suggestion that the arching and folding of mountain ranges relieves the burden on the earth's interior[2] and therefore allows the range to stand up without application of extra weight. This explanation does not account for the geodetic observations which show no extra gravity pull for the mountain ranges since the mass of material beneath the range is not changed just because it does not bear down as much on the interior. It is the mass that produces gravity pull. While this may be the cause which initiates the mountain building, something else is necessary to account for the lack of anomalies.

If we examine the history of the geosyncline and range development, we can find a possible explanation. While the geosyncline is sinking, the material in it and beneath it is getting continually more burdened and farther from the surface. If rock material may take on more compact forms as it becomes more compressed,[3] these layers under the geosyncline would be changing into denser

[1] W. Bowie, *Geographical Review*, October, 1922, p. 623.

[2] W. O. Wood, *Bull. Geol. Soc. America*, Vol. XXXIII (1922), p. 312.

[3] T. C. Chamberlin, *Jour. of Geol.*, Vol. XXIX (1921), p. 679.

form. In this process great heat would probably be evolved and would be only in part dissipated toward the surface. The heat might become so great that the temperature for forming molten rock at more moderate pressures might be reached. Presently the geosyncline becomes a zone of such weakness that the compressive forces acting on the crust will produce yielding at that point. There will be first an arching of the formations and thus a relief of the pressure on the interior. This release may make conditions at depth such that the rock will become molten. In the change to the molten condition there is considerable expansion and therefore the earth's crust may be somewhat elevated at this point and still, because of the lightness of the magma, not show positive anomalies at the surface (Fig. 1). Erosion on the mountain

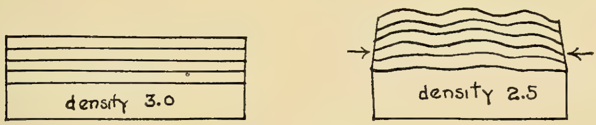

FIG. 1.—Diagrams showing the decrease in density in depth below a mountain range due to the reducing of the overburden by support from the sides and the formation of lava in place.

surface will remove weight and allow a further uplift of the higher portions without increasing the burden or the gravitative pull (Fig. 2).

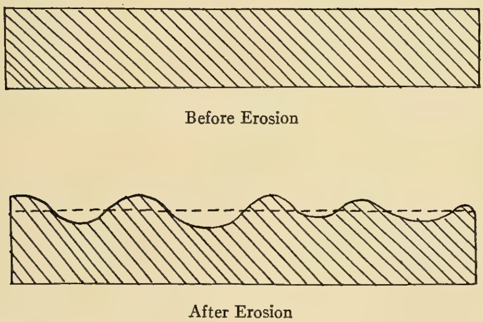

FIG. 2.—Diagrams illustrating how the top of a range may become elevated after erosion has produced irregularities. The total weight on the base is the same in each case.

THE ISOSTATIC DEVELOPMENT OF PLATEAUS

As to the development of plateaus there has been no attempt on the part of the isostasists to offer an explanation. Plateaus seem to be connected with the formation of great magmatic bodies beneath the surface. If these bodies are formed in place, the expansion could be great enough to cause the uplift without increasing the gravity. A broad arching of the crust such as occurs under plateaus might relieve the pressure sufficiently to cause a zone that was already heated to become molten. As the magma body cooled the plateau might be expected to sink, unless the erosion of the surface was equal in rate to the contraction produced by the cooling of the magmas. Plateaus are not known to have existed through long ages and are probably only temporary features.

EXPLANATION OF PENEPLAINS AND THEIR REJUVENATION

Peneplanation of mountain ranges and the subsequent uplift of these peneplains has seemed to many to be an insurmountable argument against isostasy. Even Barrell considered that peneplanation must indicate a successful resistance of the earth's crust to isostatic forces.[1] If the base of a range remains at a more or less constant elevation throughout the process of peneplanation and the range is losing weight continually by erosion, it might seem certain that it would be getting out of isostatic adjustment during the process. Bowie's answer to this objection is that a range is being constantly elevated by isostatic adjustment but not as fast as it is being eroded, because as the isostatic flow at depth continues to add material to the base of the range, it adds less material than is being substracted by erosion, because the material at the base of the column is more dense than that at the surface, and thus less has to be added to keep the column in equilibrium (Fig. 3). It seems doubtful whether this factor would be sufficient to produce peneplanation without the transference of tremendous amounts of material, probably tens of miles, because while the mountain column might be getting lower due to the adding of less material at depth, it would be getting higher due to the expansion

[1] Joseph Barrell, *Jour. of Geol.*, Vol. XXII, p. 30.

of the material produced by the relief of pressure in the erosion, and this expansion would offset much of the lowering. Neglecting the expansion factor and considering the depth of compensation as 67 miles, a difference of density of 6 per cent would necessitate erosion of some 50 miles of material to reduce to sea-level a mountain range 3 miles high.

Let us see what else could produce peneplanation. If a mountain range is being maintained in spite of erosion because of having the curvature of an arch, once this arch is broken or truncated by erosion the lateral forces will no longer be competent to support the

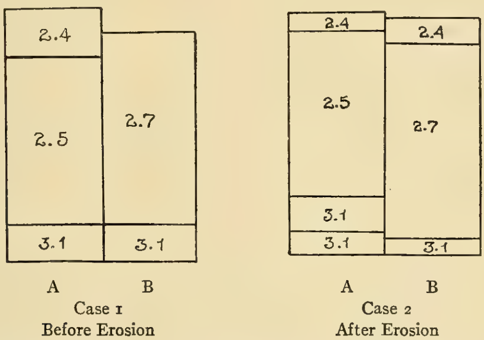

FIG. 3.—Diagrams illustrating Bowie's idea of the cause of peneplains. *A*, Mountain column; *B*, Piedmont plain column. In each case *A* and *B* are balanced in weight.

range and a peneplain may result by cessation of uplift. If the magmatic body beneath a mountain range cools or works its way to the surface, the density conditions will change and the region can no longer remain in equilibrium as a mountain range. If the lateral support which is maintaining a mountain range can be transferred to other zones of weakness, the mountain range will no longer be a rising column and erosion can soon reduce it. Thus there are several ways in which peneplains can be produced without loss of isostatic adjustment. It seems only natural that a region which is held above its surroundings by some abnormal means should be reduced to its previous level by changing conditions.

There remains to be explained the renewed uplifts of peneplains. Supposing that the peneplain was reduced by the removal of the

lateral support of the range, it is not inconceivable that the conditions would change again sufficiently to renew the support. A recurrence of vulcanism beneath the range would produce a new uplift by the expansion of the underlying material.

A CHALLENGE OF THE BASIS OF PERIODIC DIASTROPHISM

If the history of the earth actually shows periodic diastrophism and this periodicity is due to a long accumulation of strains followed by readjustment, then isostasy has not always been operative. On the other hand, if the apparent periodicity of diastrophism is due to periodic shrinkage of the interior, the isostatic condition may not be affected. However, there is perhaps some reason to question the whole idea of periodicity.

Continuity of diastrophism in the past does not mean that there was diastrophism of all parts of the crust at all times, but that the earth's crust was taking up shrinkage of the earth's interior by being constantly folded or faulted in one or several places according to the concentration of the shortening. Therefore, periodic folding in one region does not prove that diastrophism was universally periodic. Folding very likely occurred in the weakest zones of the crust. After a certain amount of shortening a zone may become more rigid and allow the folding to be transferred elsewhere.

Wide marine invasions of the lower parts of the continents are thought to indicate periods of quiet unaccompanied by diastrophism. If the shortening of the crust is temporarily transferred from the continents to the ocean basins, the folding under these basins will raise the sea-level and cause an inundation of the lower parts of the continents which will produce the epi-continental seas without a cessation of diastrophic movements.

If diastrophism has been continuous in the past, would its records of times of disturbance be equally continuous? We have a vast store of illustrations of past diastrophic movements, but in very few instances are we able to give the exact time at which the orogenic movement was initiated and the time at which it terminated. Much too often a clue as to the time of origin of one small section of a great mountain system has to be taken as the time of origin

of the entire system. Since some fairly recent mountains show evidence of several deformations we would perhaps not be wrong in concluding that mountain ranges which originated far in the past have been frequently rejuvenated. The records of times of such rejuvenations are rarely found. Added to those ranges which took up the shortening of the crust on the continents there were probably many ranges on the sea bottom which could have left no time record. Therefore, for these reasons, if we consider that the upper rectangle in Figure 4 represents continuous diastrophism, it is likely that incomplete geological records would show something of the order of the lower diagram (Fig. 4).

If we consider that individual orogenic disturbances on the average continue from one-third to one-half of a period, then the

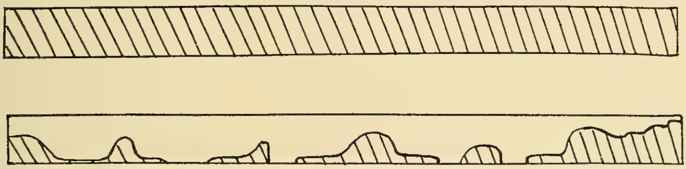

FIG. 4.—Diagrams illustrating the replacing of a complete series of deformations (above) by a fragmentary series of records (below) because of incomplete geological data.

records of the times of deformation, which have been compiled, are surprising, not in that they show infrequent deformations, but that they show an almost uninterrupted series of orogenic movements in one part of the world or another. They scarcely illustrate a contemporaneous origin of two large mountain systems. The most complete records, which are of the Cenozoic disturbances, show an almost equal distribution of diastrophism in the different divisions of the era. Only where the records have been much effaced farther back in the time scale are there indications which point toward periodicity. Even in the Paleozoic, diastrophic movements do not appear to come especially at the end of periods. In an article compiled by R. T. Chamberlin,[1] the times of Paleozoic deformation are given. A critical examination of the evidence of

[1] R. T. Chamberlin, *Jour. of Geol.*, Vol. XXII (1914), p. 315.

the exact times of these disturbances shows that out of 54 only 9 can be said with any certainty to have occurred at or very near the division between the periods, and so far as can be told from the rest they may have occurred well within one of two or even three periods. Therefore the numerous disturbances may be taken as well to indicate a continuous series of orogenic movements as an intermittent series.

Therefore the conception of periodic diastrophism should be critically re-examined and the evidence sifted with care before it can be used as an argument against continuous isostatic adjustment.

THE DEVONIAN LIMESTONE AT ST. GEORGE, QUEBEC

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An area of fossiliferous rocks which has received scant attention in the past is that of the Devonian limestone at St. George, Quebec, on the Chaudière River. In 1863, Logan[1] devoted a page or two to the limestone and its fauna, and again in 1888 Ells[2] referred to them very briefly. In the scramble to attack problems in more alluring areas geologists and paleontologists alike have passed these outcrops by. Few geologists enter the territory between the St. Lawrence River and the Maine boundary, unless it be for the purpose of examining the asbestos deposits at Thetford, or of exploring among the crystallines which outcrop along the International border. Paleontologists find little to attract them south of the fossiliferous Lévis shales along the St. Lawrence itself, and a glance at Ells's map of the country to the south shows the symbols denoting fossiliferous localities to be few and very far between. Recently B. R. MacKay[3] has published an account of these rocks in a memoir primarily concerned with the genesis and distribution of the placer gold of the region, but the stratigraphy and structure have been worked out as carefully as that difficult terrane permits. The Devonian outcrops in question have been restudied and the fauna reported on by Kindle. The writer's collection of fossils from this limestone was made during the last two years, and seems to shed some light upon the larger problems connected with the Middle Devonian.

[1] Sir William Logan, *Geology of Canada* (1863), p. 428.

[2] R. W. Ells, "Second Report on the Geology of a Portion of the Province of Quebec," *Geol. Surv. Can., Ann. Rept.* (1887), Part K, pp. 9–11K (1888).

[3] B. R. MacKay, "The Beauceville Map-Area, Quebec," *Can. Geol. Surv., Memoir 127* (1921), pp. 31–33.

The limestone is dark gray, almost black; and is crowded with fossils wherever it outcrops. It is rarely crystalline, but, upon weathering, breaks down into a rubbly mass with little dependence upon the inclosed fossils. Good opportunities for collecting are therefore rather unusual, except on the weathered surfaces. Whole specimens of brachiopods were not collected as such at the outcrops, but were worked out in the laboratory. The corals, on account of their much greater size, could be collected whole, the limestone disintegrating around them. A day's search failed to reveal any trilobites, although they have been reported before. The brachiopods were almost exclusively of two species; what was the relative abundance of the species collected by Logan and by Ells is not stated in their reports. There is no doubt, however, about the Onondaga age of the fauna. This will be shown by the following list and descriptions of fossils recently collected by the writer.

COELENTERATA

Favosites basalticus (Goldfuss)[1]

One of the most abundant species present. The specimens are in every way characteristic. Although Ami is reported as having recognized *F. gothlandicus* from this locality, not a single specimen in our collection can be placed in that species. Every individual examined (a score or so) lacks spines within the corallites, but there are many squamulae between the tabulae. The presence of spines has often been considered an evidence of the Silurian age of a Favosites, whereas squamulae are characteristic of Devonian species.

Diphyphyllum arundinaceum (Billings)[2]

One of the most striking characteristics of our specimens is the wide spacing of the strong simple tabulae. There are from six to eight of these in each 10 mm. The corallites seldom reach 10 mm. in diameter. More often they are less than 8 mm. The largest specimen is 21 cm. from "root" to the outermost calyx.

[1] L. M. Lambe, *Geol. Surv. Can., Contr., to Paleon.*, Vol. IV (1899), Part I, p. 8. Full lists of references are not given. Only those most easily accessible to students are included.

[2] Lambe, *ibid.*, Part II, p. 162; H. A. Nicholson, *Paleontology of Ontario* (1874), p. 34.

Cyathophyllum sp.

Great numbers of corals belonging to this genus occur at this locality, but none of them shows specific characteristics. It is probable that two, or even more, species are represented in the collection.

Cystiphyllum vesiculosum (Goldfuss)[1]

One specimen only of this species was collected. It is typical in all respects, except that it is not complete enough to show the calyx.

Zaphrentis Rafinesque and Clifford sensu stricto[2]

One specimen of a Zaphrentid coral with a well-developed fossula, and with septa (not carinated) extending fully to the center of the visceral chamber, is present in the collection. It consists of little more than a cross-section, so that nothing can be said of its external form. In the collection made by Logan and examined by Billings, an unidentified Zaphrentis was listed.

Amplexus cf. hamiltoniae Hall.

Two small specimens are placed provisionally in this species. In both, the external ornamentation is preserved exceptionally well, but almost all traces of internal structure have been obliterated by the crystallization of the interior. Septa may be seen within one specimen, closely crowded, and produced about a quarter of the distance from the outer wall to the center, but whether these represent the original length, or only such parts as have escaped crystallization is uncertain.

Syringopora tabulata (Milne-Edwards and Haime)[3]

This is one of the largest corals found at St. George, rivaling *Favosites basalticus* in size. Some of the specimens, incomplete, weigh as much as 15 pounds, and are 40 cm. on their greatest diameter. Ami has identified *S. hisingeri* from this locality, but none of our forms belongs to that species. In all of our specimens, the corallites are never separated by spaces greater than their own diameter, and the connecting tubes are disposed at uniform levels.

Stromatopora Goldfuss (emend. Nicholson)[4]

[1] M. Edwards and Haime, "Mon. Brit. Corals," *Paleon. Soc. London* (1850), p. 243; Lambe, *op. cit.*, Part II, p. 192.

[2] M. O'Connell, "Revision of the Genus Zaphrentis," *Ann. of the New York Acad. Sci.*, Vol. XXIII (1914), pp. 188–89.

[3] C. Rominger, *Geol. Surv. Mich.*, Vol. III (1876), Part II, p. 84.

[4] H. A. Nicholson, "Mon. Brit. Stromatoporoids, *Paleon. Soc. London* (1886), p. 91.

Our specimens are all of a gently undulating, flattened form, but much of the structure has been destroyed by weathering. This condition is not confined to the surface, for much of the internal structure of the fossil is now indistinct. Beyond a rugosity developed somewhat concentrically within a slightly upturned margin, there are no surface markings of distinctive value. The best natural section of the skeleton shows very fine corrugations spaced $4\frac{1}{2}$ per millimeter. These appear upon a polished surface as lines of black dots crossing the white calcite. It may be that these dots represent the junction of radial pillars with the laminae, but neither pillars nor laminae have been preserved. The same structure is expressed on weathered edges by extremely fine ridges. Under these circumstances, specific identification is impossible, and even generic determination is largely a matter of conjecture. Our specimens are from 10 to 24 mm. thick, and the largest fragment is 34 cm. across. This was broken from a whole specimen which was more than 2 feet across.

BRYOZOA

Three or four species occur in the collection, but I have not attempted their identification. They are for the most part Fenestellids.

BRACHIOPODA

Stropheodonta sp.

The interior of a pedicle valve of a species belonging to this genus is present in our collection. It has no characteristics of specific import.

Atrypa reticularis (Linné)

Abundant. Our specimens vary in form from those in which the valves are equally convex to those in which the pedicle valve is almost flat. They are all rather small, seldom attaining a width or a length of 20 cm.

Spirifer lucasensis Stauffer[1]

Much more abundant than *Atrypa reticularis*. Our specimens are identical with those from Ohio, save that in some the hinge line is a little less than the greatest width of the valves. Inasmuch

[1] C. R. Stauffer, *Geol. Surv. Ohio., Bull. 10* (1909) fourth series, pp. 188–89, Pl. 16, Figs. 1–5.

as our specimens show all gradations between such a form and another in which the hinge line exceeds the greatest width of the valves, I have assumed that this variation is of minor importance. The significance of the association of this species, which in Ohio occurs in beds of Hamilton age, with true Onondaga corals, is discussed below. This is probably the species identified by Billings, Ami, and Kindle as *S. gregarius* Hall. Stauffer has suggested that two of Hall's figured specimens of that species[1] may belong to *S. lucasensis.*

GASTEROPODA

Igoceras cf. conicum (Hall)
Igoceras cf. plicatum (Conrad)

Fragmentary representatives of this genus were collected at St. George, and tentatively assigned to the species suggested above.

THE AGE OF THE LIMESTONE

There is an apparent contradiction in the evidence presented by the fossils. All of the corals definitely identified are typical Onondaga species, and as they far outnumber, both in species and in number of individuals, the representatives of other phyla, we may assume for them a higher diagnostic value than for the other fossils. In fact, there is but one other fossil with any diagnostic value in our collection—*Spirifer lucasensis*, which has previously been reported from the Delaware formation (the equivalent of the Hamilton and Marcellus beds) of Ohio. The Columbus limestone, which underlies the Delaware formation, is rich in corals, and is the western equivalent of the Onondaga. Corals do occur in the Delaware, but they are not characteristic of that formation. Since the Delaware postdated the Onondaga of Quebec, *S. lucasensis* is evidence of a faunal migration westward near the end of Onondaga time. At about this time the St. Lawrence channel was permanently closed, and a retreat of the waters from the maritime provinces westward ensued. Such a retreat could not promote a continuance of the clear waters which the Onondaga fauna predicate; in fact, in the sediments immediately succeeding this event we have

[1] James Hall, *Paleontology of New York,* Vol. IV, Pt. I, Pl. 28, Figs. 9–10.

evidence of muddy waters, in which the coral fauna was extinguished. Other forms, more hardy, or less susceptible to slight changes in their habitat, could migrate with the retreating sea. In Indiana, Ohio, and Michigan clear-water conditions prevailed throughout the Middle Devonian, so that the presence there of a somewhat restricted coral fauna above the Onondaga is not surprising. It is supposed that *S. lucasensis* took part in this westward migration, reaching the northwestern part of the Ohio Basin in Hamilton time.

EXTENT OF THE ONONDAGA SEA

The association of typical Onondaga corals with a brachiopod found in the Hamilton of Ohio suggests one minor readjustment of the paleogeographic maps of the continent in Onondaga time. *Spirifer lucasensis*, originating in the East, migrated to Ohio by some path no trace of which has to date been reported. In spite of the intensive search for fossils in the Devonian rocks of New York State, this Spirifer has not been found. It seems probable, then, that this fossil did not follow along the line indicated by the present outcrops of Onondaga in New York from the Helderbergs westward. A glance at Schuchert's paleogeographic map for the late Onondaga, or at the map for Onondaga time in Grabau's *Text-Book of Geology*, shows a land area bordered approximately by Lake Huron on the west, the Hudson-Champlain line on the east, the present Onondaga outcrops on the south, and unlimited to the north. Inasmuch as all of this area south of the forty-fifth parallel was certainly covered by Ordovician sediments, which probably extended as far north as Lake Temiskaming, it does not seem improper to suppose that the Onondaga sea also covered much of it. If the strand line be drawn from Montreal westward along the forty-fifth parallel to Lake Huron, we shall have a much more probable distribution of land and sea than the maps show. Coral faunas require a wide, open seas, rather than narrow channels. It is a question how close to an outcrop of Onondaga limestone one can draw the strand line. In this case, the cartographer may be allowed more latitude than when dealing with detrital rocks. Such a boundary as suggested would remove from the present maps the

objection that the long line of Onondaga outcrops in New York borders too closely a land mass, and would provide the clearer, off-shore sea which the fauna seems to require. And, moreover, it would provide a pathway, all traces of which are now obliterated, for the migration of *Spirifer lucasensis.*

A paleogeographic map of North America during Onondaga time is submitted with this report. It will be seen that the distribution of lands and seas is shown on a much more simple plan

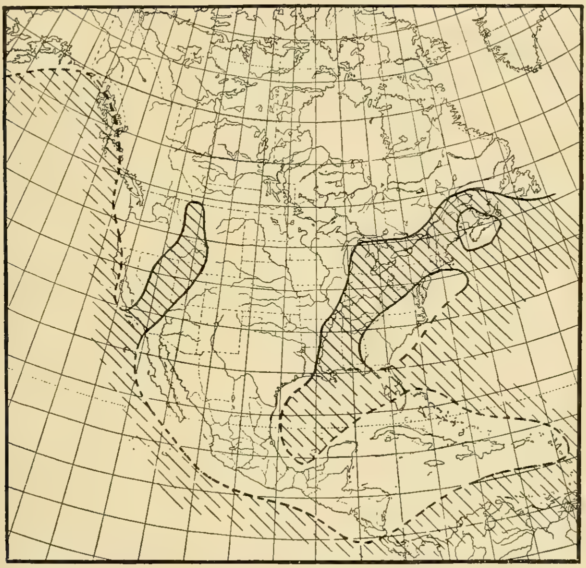

FIG. 1.—Paleogeographic map of North America during Onondaga time. Shaded areas represent seas.

than in most maps representing the geography during this period. Simplicity, when compatible with the facts, is desirable in our necessarily crude reconstructions of the continent. In this respect the paleogeographic maps in Grabau's *Text-Book of Geology* are inferior to their predecessors, for their complicated shore lines are apt to give students the idea that our knowledge of paleogeography has reached that stage of perfection in which shore lines can be plotted accurately and in detail. Such is not the case, nor is it ever likely to be; so that for both scientific and pedagogical

reasons we should use, in general, easy-flowing lines such as those which characterize Schuchert's paleogeographic maps.

The St. Lawrence Channel was open for the greater part if not all of Onondaga time. The northern shore line from Montreal west to Lake Huron is drawn in accordance with the conclusions reached above. In Dunbar's map,[1] this shore line is placed much farther south, probably through inadvertence, there being no reason for showing a land area on the site of the long east and west outcrop in New York. The irregularities in the shore line around the Great Lakes and to the south[2] are omitted, for some seem not to be well founded, and none is essential. The western shore line of southern Appalachia is removed somewhat eastward, in order not to embarrass the coral faunas of western Tennessee and Kentucky.

The "New Jersey Strait" is not represented on the present map, but instead there is a wide sea-way traversing southern and central New England. In general, a wide strait is preferable to a narrow one, and, in particular, it seems unlikely that there was a sea-way across New Jersey, on account of the great thicknesses of delta deposits which accumulated there only a few epochs later. If there is an error in the position of this New England Channel, it is probably that it lies too far south.

From the Onondaga onward, Appalachia began to rise and to extend northward. By the close of Onondaga time, it had effected a junction with the island across the New England Channel, thereby closing it. It has been supposed that the St. Lawrence Channel was closed at the end of the Onondaga, and this is probably correct. The rising Appalachia was later to shed the enormous amount of sediment comprised in the Upper Devonian deltas of the northern Appalachian region. With the St. Lawrence and the New England channels closed, subsequent invasions of European faunas must be explained as having come by way of the Arctic rather than by the Atlantic Ocean.

The Cincinnati dome is not represented as an island upon this map, because it was probably covered much, if not all, of the time

[1] Carl O. Dunbar, "Stratigraphy and Correlation of the Devonian of Western Tennessee," *Geol. Surv. Tenn., Bull. 21* (1919), Fig. 3B.

[2] See Stauffer, *op. cit.*, Pl. 14.

by the Onondaga sea, for as Miller states[1] "in the succeeding Middle and Upper Devonian submergence, sediments were laid down unobstructedly and with great horizontality across the Arch," though this conclusion has been questioned.

The shore line in western United States is copied from Schuchert's map. There is some doubt as to the Onondaga age of the outcrops on which this shore line is based, and there seems to be no good reason for placing the Onondaga shore line so far west of the present strand, but those are subjects with which this paper is not primarily concerned.

[1] A. M. Miller, "The Geology of Kentucky," *Department of Geology and Forestry of the State of Kentucky*, *Bull. 2* (1919), fifth series, p. 77.

DID CRATER LAKE, OREGON, ORIGINATE BY A VOLCANIC SUBSIDENCE OR AN EXPLOSIVE ERUPTION?

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The great volcanic eruption of 1912 at Katmai, Alaska,[1] has again called the attention of geologists to Crater Lake, Oregon, with the suggestion of a similar explosive origin of the great depression containing that lake, which depression had previously been ascribed by the present writer[2] to subsidence.

Crater Lake is in a deep abrupt basin about 5 miles in diameter and 4,000 feet deep in the plateau-shaped summit of the Cascade Range.

Crater Lake is completely encircled by a very bold rim which rises to approximately 2,000 feet around the lake, which is about 2,000 feet deep. The rim has a very steep slope inside toward the lake but a gentle slope outside to the summit-plateau on which Mount Mazama was built up by many successively overlapping lava flows and sheets of ejected volcanic fragments, all erupted from practically the same volcanic orifice.

Nearly all this rim, however, was built up by eruptions of andesite before the eruptions of dacite began.

Much dacite-pumice formed a partial top-rim of Crater Lake, but the succeeding dacite flow from the summit of Mount Mazama finally broke from the surface of the lava tunnel at Rugged Crest and overflowed down the inside of the rim into the head of Cleetwood Cove of Crater Lake as Mount Mazama sank away into engulfment, leaving the outer slope of the rim with its fresh flow of dacite and the glaciated rim with its glacial striae and moraines, as shown on the map, Figure 13, *Geological History of Crater Lake National*

[1] Robert Fiske Griggs, *The Valley of Ten Thousand Smokes.* The National Geographical Society, 1922.

[2] "Geology of Crater Lake National Park 1902," *U.S. Geol. Survey Professional Paper No. 3.* Also *Geological History of Crater Lake National Park.* Dept. of Interior, 1912.

Park, 1912, entirely uncovered by any material that could have been blown out from Mount Mazama to make the great depression for Crater Lake if Mount Mazama was *blown away à la Katmai* and *not engulfed*.

The most striking evidence of the engulfment of Mount Mazama is afforded by the inflowing stream of dacite, Fig. 1, from the notch produced by the cave-in at Rugged Crest down the inner

FIG. 1.—The inflow of dacite at Cleetwood Cove of Crater Lake

slope of the rim to Cleetwood Cove of Crater Lake. The view shows the whole length of the inflow from the notch of Rugged Crest to the shore of the lake, and it appears that Mount Mazama sank away about the time the final flow of dacite occurred, for the dacite beneath the crust at Rugged Crest was still soft enough to flow and to cause the crust to break and cave in. The broad flow of dacite from Rugged Crest northeast down the outer slope of Mount Mazama is shown in Figure 1, also the short flow inward to the lake.

AN IMPROVED RECORDING MICROMETER FOR ROCK ANALYSIS

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Numerous methods have been devised for the quantitative estimation of the mineral composition of rocks by measurement of the minerals appearing in thin sections. These have been described in detail elsewhere,[1] and it is not the writer's purpose to consider their relative merits at length. All these methods involve the measurement of areas either directly or by weighing dissected rock patterns, or of intercepts of the several minerals along certain selected lines. In any case, the number of measurements must be large in order to overcome the errors due to variation in grain size and irregularity of distribution of the minerals, and the process by any one of the methods is a somewhat laborious one. Among the several methods, that of Rosiwal seems to combine the requisites of simplicity and relative accuracy. This method has been the subject of careful examination by Johannsen and Stephenson[2] from the empirical standpoint, and by Lincoln and Rietz[3] from the theoretical as well as the experimental point of view. The work of these investigators proves adequately the validity of the method, and that of Lincoln and Rietz is valuable particularly in offering the means of defining somewhat accurately the requisite number of measurements for a given degree of precision in results obtained under various conditions.

[1] A. Johannsen, *Manual of Petrographic Methods* (New York, 1914), pp. 290–92, and "A Planimeter Method for the Determination of the Percentage Compositions of Rocks," *Jour. Geol.*, Vol. XXVII (1919), pp. 276–85; A. Holmes, *Petrographic Methods and Calculations* (London, 1921), pp. 310–22; J. Hirschwald, *Handbuch der bautechnischen Gesteinsprüfung* (Berlin, 1912), pp. 146–47, 163–72; A. Rosiwal, "Über geometrische Gesteinsanalysen," *Verh. der k. k. geolog. Reichanstalt* (Wien, 1898), No. 5.

[2] A. Johannsen and E. A. Stephenson, "The Rosiwal Method for Minerals," *Jour. Geol.*, Vol. XXVII (1919), pp. 212–20.

[3] F. C. Lincoln and H. L. Rietz, "The Determination of the Relative Volumes of the Components of Rocks by Mensuration Methods," *Econ. Geol.*, Vol. VIII, pp. 120–39.

Their work, as well as that of other students, indicates the need of large numbers of measurements to insure results of requisite accuracy, and the usefulness and popularity of the Rosiwal method depends upon the simplification and standardization of the mechanical and numerical operations involved. This was recognized in 1916 by Shand,[1] who described a recording micrometer which served both to make the measurements and to add the resulting figures. This instrument, which can be attached to the stage of any petrographic microscope, saves the large amount of labor and eye strain previously involved in the adding of the data as well as in the concurrent recording and observation. It has, however, one important defect, as Shand himself recognized,[2] in that it can be used to measure but two constituents at a time (any one mineral and the remainder of the rock). In case more minerals are to be estimated, it is necessary to repeat the operation.

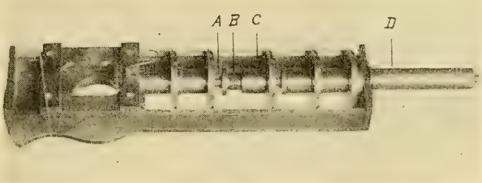

FIG. 1.—Improved recording micrometer. *A* is a square rod, *B* is a screw with an axial square hole which fits *A*, *C* is a nut and dial fitting the threads of *B*, *D* is the housing of a tension spring which pulls the slide carriage toward the right. Parts slightly separated to show relations of *A*, *B*, and *C*. Normally the spring keeps these together.

Having occasion recently to make a number of such estimates of rock composition, and needing some sort of device to do the work, the writer found it possible to overcome the limitation of the Shand micrometer by the mechanical device shown in Figure 1. This was constructed by Mr. Stanley Price, mechanician, of the State University of Iowa, according to the writer's specifications. It consists essentially of a single sledge which is actuated by a series of screws and nuts arranged in a string on a square rod at one side. The screws are free to slide but are prevented from turning by the square hole by which each is fitted to the square rod. The nuts consist of the threaded sleeve and a graduated dial by which their motion is recorded. The position of the sledge, which is held against

[1] S. J. Shand, "A Recording Micrometer for Geometrical Rock Analysis," *Jour. Geol.*, Vol. XXIV (1916), pp. 394–404. [2] *Ibid.*, p. 399.

the string of screw-nut pairs by a spring, is determined by the total length of the string. The latter is adjustable by rotating any one of the several nuts. Thus, the sledge carrying the rock section may be driven across the field of view by turning the appropriate dial in crossing the part of the section occupied by each of the several minerals. Thus, as many minerals as desired may be measured, recorded, and the results added, in one operation. The instrument, as constructed for the writer, carries five dials, but any number may be added by increasing the length of the machine. In order to avoid the necessity of having an exceptionally strong backlash spring, it is found desirable to traverse the sections in the same direction by increasing the length of the string of screw-nut pairs. With this precaution, which is good practice with any instrument of this sort, the micrometer as shown gives excellent results. The Bausch and Lomb Optical Company has the necessary data for constructing duplicates of this instrument and will furnish estimates on request. The following measurements of the minerals of a thin section of granite will serve as an example of its performance.

TABLE I

INSTRUMENT READINGS—TRIAL I

Quartz	Feldspar (Chiefly Orthoclase)	Biotite	Apatite
527	291	00	68
466	592	00	113
283	1,207	54	00
387	1,221	00	00
718	853	136	00
1,152	605	158	72
418	954	530	54
795	873	240	00
629	1,255	47	00
645	1,088	103	00
593	857	95	00
770	760	15	00
747	757	00	28
405	732	13	145
174	605	00	00
8,709 (37.55%)	12,650 (54.40%)	1,391 (5.99%)	480 (2.06%) 1,391 12,650 8,709
Total......	....	....	23,230

Each trial consists of fifteen transepts of the section at intervals of one millimeter, the second series starting one-half millimeter nearer the edge of the section so as to occupy positions staggered with those of the first series. Each transept crosses an average of about ten mineral grains. The measurements, readings, and recording of totals for the transepts were completed for each trial in about thirty-five minutes.

TABLE II

INSTRUMENT READINGS—TRIAL II

Quartz	Feldspar (Chiefly Orthoclase)	Biotite	Apatite
483	455	00	168
265	940	66	00
423	1,162	00	00
416	1,191	00	00
1,023	703	57	00
758	582	279	249
504	815	476	58
862	1,025	54	00
518	1,287	122	00
700	1,096	93	00
675	649	124	00
824	767	28	00
726	662	00	61
301	785	13	80
45	475	00	00
8,523 (37.00%)	12,594 (54.55%)	1,312 (5.69%)	616 (2.67%) 1,312 12,594 8,523
Total......	....	....	23,045

It will be seen that there is rather good agreement in the results for the three more abundant constituents but less satisfactory agreement in the percentages for the apatite. Considering the scarcity and irregular distribution of the mineral, this result is not surprising and is only to be improved by a much larger series of measurements.

Although the writer has never used an instrument of the Shand type, he is confident that the instrument here described can be handled with equal facility in any kind of measuring operation and has the important additional advantage of permitting simultaneous estimation of any number of constituents with the resulting economy

of time. In case one wishes to identify a mineral grain between crossed nicols, the instrument can be rotated through more than 270 degrees of the motion of the stage (Fig. 2). Certain improvements occur to the writer which might be followed by anyone wishing to duplicate the instrument. The one constructed for the writer weighs about twenty-one ounces. The use of aluminum-zinc alloy instead of brass for certain parts and attention to details of design would probably result in reducing this weight by nearly one-half. The substitution of celluloid dials and black graduations for the brass dials on the instrument shown would greatly increase the ease of reading the instrument. In the present instrument, whole turns are read by counting threads exposed or by measuring with a scale; a thin scale could easily be added to each screw by means of which these could be read at once. The pitch of the screws ideally should be 1 millimeter and the graduations of the dial .01, though in practice the graduations of the model, which are .008 mm., are equally satisfactory, since computations are wholly relative.

Fig. 2.—Micrometer mounted on stage of Leitz petrographical microscope.

THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION AND MAGMATIC DIFFERENTIATION OF IGNEOUS ROCKS

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VII

VISCOSITY, SIZE OF CRYSTALS, SPEED OF CRYSTALLIZATION, FORMATION OF GLASS, INFLUENCE OF TIME, UNDERCOOLING (OR SUPERSATURATION), AND EQUILIBRIUM OF MIX-CRYSTALS BETWEEN THE SOLID AND LIQUID PHASE, ETC.

We have only empirical methods for the measurement of *viscosity*, e.g., submersion of a ball of a certain weight for a certain period, resistance to stirring, the length of an out-pulled thread, etc.

At one and the same temperature the various silicate melts (at one atmosphere pressure) are characterized by greatly varying viscosity.[1] To be convinced of this, laboratory experiments are not needed, as we only need to refer to the well-known phenomena seen in the large, molten masses at smelting-plants, glassworks, etc. As I have had a rather considerable experience in this matter for the judgment of the temperature supported by measurements with Le Chatelier's and optical pyrometers, I shall give a review of the degree of viscosity of various silicate melts, mainly metallurgical slags and several glasses.

At first, according to an old experience that is also confirmed by laboratory measurements, we notice that the viscosity decreases with increasing temperature, though in a highly varying degree for the various melts.

[1] Cf. especially E. Greiner, "Ueber die Abhängigkeit der Viscosität in Silikatschmelzen von ihrer chemischen Zusammensetzung," Ing Diss., Jena, 1907 (with references to the previous literature). Further the chapter "Ueber die Beziehung zwischen Viskosität, Krystallizationszeit und Krystalgrösse" and "Weshalb ist das Glas eine feste Lösung?" in *Silikatschmelzlösungen* 1904, I, 156–69, besides earlier treatises by J. H. L. Vogt, especially one in *Zeitschrift für praktische Geologie* (1893), p. 275.

Extremely thin.—Basic slags with predominant MnO, as

SiO_2	MnO	FeO	Al_2O_3,	CaO,	etc.
30–45	30–40	5–25	0–4		

With the exception of certain silicate melts rich in PbO, melts rich in MnO are the thinnest silicate melts I know, and they are also extremely thin at the temperatures immediately above or at the beginning of crystallization (of manganese-fayalite or rhodonite). In the common silicate slags with as much MnO as 10–15 per cent, MnO causes a noticeable increase in thinness.

Exceedingly thin.—Basic slags with predominant FeO, as

SiO_2	FeO	CaO,	MgO,	Al_2O_3	
25–30	60–70	$\underbrace{\qquad\qquad\qquad\qquad}_{3-10}$			etc.

These are also very thin, even when cooled to the beginning of the crystallization (of fayalite).

In slags with predominant FeO, the viscosity is somewhat greater when the percentage of SiO_2 rises to 40–45 per cent, and the viscosity is considerably increased when the percentage of SiO_2 rises above 55 per cent.

In the common CaO+MgO slags with some Al_2O_3, FeO causes an increase of thinness, hardly however to the extent shown by those with MnO.

Very thin at about 1,400°.—Middle basic melts with approximately equal proportion of CaO and MgO,

SiO_2	CaO	MgO	Al_2O_3	MnO+FeO
30–40	30–40	20–30	0–5	0–4
40–45	30–40	10–20	2–7	0–4
40–45	15–30	20–30	2–7	0–4

The thinness seems to increase somewhat when CaO is replaced in part by MgO. This may not be maintained with absolute certainty, however.

In an intermediate mixture of CaO and MgO, the viscosity increases with increase of SiO_2, when SiO_2 amounts to more than 50 per cent.

Thin at 1400°.—Silicate melts with

SiO_2	CaO	MgO	Al_2O_3	FeO, Mno
50	25–30	15–20	2–5	1–3

Further, melted diopside

SiO_2	CaO	MgO
55	26	19

But when SiO_2 amounts to 60–65 per cent, as

SiO_2	CaO	MgO	Al_2O_3
60–65	20–25	about 10	about 5

the molten masses are *rather* viscous. And with still more SiO_2 and decreasing CaO+MgO, the degree of viscosity is *considerably increased* so that with about 75–80 per cent SiO_2, even at temperatures as high as 1500°–1600°, a very considerable viscosity is involved. As to pure SiO_2, see below.

Al^2O^2-bearing silicate melts.—A few per cent of Al_2O_3 seem to have no traceable influence on the viscosity of basic silicate melts with predominant CaO, MgO, FeO, etc. Basic slags with somewhat higher percentages of Al_2O_3, as

SiO_2	Al_2O_3	CaO	MgO
30–35	15–25	30–40	5–10

wherein melilite-gehlenite (with spinell, etc.) crystallizes to a considerable extent, seem throughout to be rather thin at a temperature about 1400°. (As to anorthite see below.)

If we pass to somewhat more *acid* slags, we find that Al_2O_3 induces considerable viscosity. Thus slags, as e.g., the Mansfelder slags with

SiO_2	Al_2O_3	CaO	FeO	K_2O
46–50	16–18	16–22	4–6	4

at a temperature as high as 1500°–1550°, are fairly thin but become very viscous even at about 1300°, some 100° above the beginning of crystallization.

The same also applies to slags as

SiO_2	Al_2O_3	CaO	MgO	FeO
46–50	14–18	7–13	3–5	about 20

which at about 1300°–1400° are rather viscous in spite of the high percentage of FeO.

Feldspars.—According to the investigations of the Geophysical Laboratory of the Carnegie Institute, orthoclase (microcline) and albite are characterized by extremely high viscosity just above the melting-point. It is so great, and at the same time the speed of the melting so slow, that these minerals, as well as quartz, may be superheated for a while to some degrees above the theoretical melting-point without melting.[1] On account of the extremely high viscosity of microcline, this mineral has for more than 100 years been used as a glaze for porcelain. Melted microcline is extremely viscous, even when heated to several hundred degrees above the melting-point.

Melted anorthite (melting-point 1550°), on the other hand, just above its melting-point is medium thin, both according to the experiences of the Washington Institute and of myself. The melts lying between Ab and An show intermediate viscosity.

Melted *SiO_2* is extremely viscid, and silicate melts with more than 60 per cent SiO_2 and the remainder mixtures of various bases (CaO, MgO, FeO, Al_2O_3, etc.) show increasing viscosity with increasing percentages of SiO_2.

In short, numerous observations indicate that the viscosity which at a certain temperature characterizes a complex silicate melt containing several components, as SiO_2, $KAlSi_3O_8$, $NaAlSi_3O_8$, $CaAl_2Si_2O_8$, $CaMgSi_2O_6$, etc., may be *derived from the viscosity which is characteristic of each of the components.* But the viscosity is hardly a linear function of the viscosity of the components.

As to the *alkali-silicates*, we refer to the investigations of Greiner. Here it may be pointed out, however, that K_2SiO_3 (alone or with an admixture of SiO_2) is considerably more viscous than the corresponding soda-silicate, and potassium-glass is, as is known, considerably more viscous than soda-glass. According to Greiner,

[1] See Day and Allen's well-known Feldspar studies (1905).

FeO, MnO, Fe_2O_3, and MgO (in the order mentioned) reduce the viscosity of $Na_2SiO_3 \cdot SiO_2$, while CaO and Al_2O_3 increase the viscosity (Al_2O_3 most strongly).

Applied to petrography it will appear from the above that melted (anhydrous) granite, quartz-porphyry, rhyolite, and obsidian at one atmosphere pressure are extremely viscous, even heated to 100°, 200°, or 300° above the beginning of the temperature of crystallization.

Molten (anhydrous) alkali-syenite, trachyte, and phonolite are still rather viscous, presumed one atmosphere pressure. Molten (anhydrous) gabbros are somewhat more thin, and basalts and related rocks rich in iron are rather thin.

The statements above are valid for molten anhydrous masses, or generally molten masses without dissolved light volatile compounds,[1] at one atmosphere pressure.

As to the *direct influence of the pressure*, reference may be made to Johnston and Adams in the *American Journal of Science*, XXXV, 226–31. The result is "that the effect of uniform pressure is always to increase the viscosity (water and certain dilute aqueous solutions, both of low temperature, excepted)."

According to this it must be supposed that the direct effect of the pressure is to increase the viscosity of the silicate melts. However, more important in many cases is the *indirect* effect of the pressure since the content of the magma of *dissolved light volatile compounds* is increased with the pressure, and these volatile compounds (H_2O, etc.) reduce the viscosity to a very considerable degree.

This applies especially strongly to granitic magmas which according to geological experience must have been rather thin, and still more to granite-pegmatite magmas which even at so low a temperature as about 700°–800° must have been especially thin on account of their relatively rich content of H_2O, etc.

The effusives, on the other hand, must as a rule have contained much less H_2O, etc., and their degree of thinness, at least in many

[1] I do not here take into consideration that the silicate slags from, e.g., a blast furnace or a matte-smelting contain dissolved a very small quantity of gas, which at least to a substantial extent escapes partly before the beginning of the crystallization and partly on an early stage during the process of crystallization.

cases, may be measured approximately by the viscosity valid to the dry melts.

According to this we find that basalt magmas commonly have flowed out in quite thin streams, which may have covered very large areas, even several tens of thousands of square kilometers, while acid rocks, especially rhyolites and related acid effusives, often, but not always, form domes.

We will here also mention another point of great geological importance. As maintained by R. A. Daly in his *Igneous Rocks and Their Origin* (1914), among the *deep-seated* rocks the *acid* rocks (granite and granodiorites) have an extension several times as large as the basic rocks (with the gabbros as the most important representative). The contrary is the case with the *effusives* since here *basaltic* (and pyroxene-andesitic) rocks quantitatively are much more important than rhyolites. I consider from my own geological experience, that Daly is right in this view, but I do not agree with Daly's explanation.

We must suppose that the magmas of the granitic deep-seated rocks generally contained a much larger quantity of the light volatile compounds than the magmas of the gabbroic rocks, and consequently that the temperature at the beginning of crystallization compared with that of the anhydrous melts was decreased much more for the granites than for the gabbros.[1]

When an *acid* (or granitic) magma, at the temperature of the upper limit of the crystallization interval (see the next chapter), comes under a lower pressure, by the passage to the surface of the earth, a great part of the light volatile compounds will escape. By this the temperature of crystallization increases and at the same time also the viscosity increases; the latter even to a considerable degree. The magma, in the first stages of crystallization will under these circumstances become so little movable or so viscous that part of it will never reach quite to the surface, and part of it will do so only under favorable conditions. For the *basic* (gabbroic or basaltic-andesitic) magma we must also assume some escape of the light volatile compounds by the passage to the surface. This is of less importance, however, since the volatile components here

[1] See their *Journal* for 1922, pp. 664–71.

were present in smaller quantities. In addition to this, as the crucial point is the fact that basic magmas with relatively small or no content of light volatile compounds are considerably more fluid than are the acid with the same amounts. Thus the basic magmas, even if they were much less extended in the deep-seated basins than were the acid, must reach the surface in much greater quantity and form much larger flows.

The anorthosites and the almost pure olivine rocks (dunites), according to my opinion, must be explained by the extremely high temperature of crystallization of these rocks. The magmas would consequently be cooled at once to quite advanced crystallization as they were pressed as dikes into the surrounding colder rocks. Thus the magmas of these rocks could not get to the surface and could consequently not form flows.

As treated in my work *Die Sulfid-Silikatschmelzlösungen* (1917), molten FeS, alone or with some NiS, PbS, Cu_2S, etc., is characterized by being considerably thinner than even the thinnest silicate melts. As to the geologic consequences of this, I refer to my earlier publications on the genesis of the nickel-pyrrhotite deposits.

ON THE SIZE OF CRYSTALS AND THE RATE OF CRYSTALLIZATION

Many investigators in their synthetic experiments have confined themselves to melts in a platinum crucible with a comparatively small quantity of silicate as, e.g., 10–20 gm. (or about 4–8 cm.^{3}). In consequence only quite small individuals have resulted, thereby producing a wrong conception of a slow rate of crystallization for the rock-forming minerals.[1]

If we wish to obtain from experiments a correct idea as to the size of the minerals and the rate of crystallization, we must operate with sufficiently *large* molten masses. Even with a duration of crystallization of only half an hour we may get *very large* crystals,

[1] For example we may quote C. Doelter, *Phys. chem. Mineralogie* (1905), p. 108: "Unter normalen Verhältnissen würde ein etwa 10 bis 20 mm. langer Augitkrystall unter der Voraussetzung dass die Krystallizationsgeschwindigkeit pro 1 Minute 0.001–0.002 mm., wie es die meisten Versuche ergeben, beträgt, 200 Stunden brauchen." In fact, the rate of crystallization for augite (diopside) from a pure melt, as will be discussed below, is about 1 mm. (along the *c* axis) per minute, thus 500–1,000 as much as indicated by Doelter.

assuming (*a*) that the crystallization takes place in a very thin fluid silicate melt, and (*b*) that the mineral crystallizes from a solution that is of a percentage of 100, 90, 80, or at least not below 70.[1]

I will give some measures of the size of crystals in some smelting products, slags, etc.

Diopside.—In one of my earlier melting experiments with almost iron-free $CaMgSi_2O_6$ (containing at most 1.5 per cent FeO), thus in a melt of practically 100 per cent of $CaMgSi_2O_6$, the time of crystallization (at 1336°) of a melt of 16 kg. (16,000 gm.), according to pyrometer measurements, amounted to thirty-one minutes. There resulted, hereby, individuals of a length of 30 mm. ($\pm c$), locally, perhaps, a little longer, and in druses were found freely developed columnar crystals 25 mm. long parallel to *c*, 9–10 mm. parallel to *a*, and 7 mm. parallel to *b*.

In the common iron furnace, slags cast in slag-stone molds about $0.4 \times 0.3 \times 0.25$ m. in size, where the crystallization according to pyrometer measurements requires about thirty to forty minutes, I found in slags with about 75–80 per cent augite, freely developed crystals of diopsidic augite 18–20 mm. long parallel to *c*, 9–11 mm. parallel to *a*, and 6–8 mm. parallel to *b*.

Pseudowollastonite.—A melting experiment performed by me, in melting 3.5 kg. of pure $CaSiO_3$ (with a time of crystallization of about fifteen minutes), gave as a result thin tabular crystals 18 mm. long measured parallel to the base, with some individuals a little longer.

In slags with about 60–70 per cent pseudowollastonite with a period of crystallization of about thirty minutes, thin tabular crystals with a base of a length in one case of 7 mm. and in another case of 8 mm. were freely developed.

The melilite minerals.—The largest melilite crystals and the largest slag crystals that I have seen, on the whole, I found in 1913 in a basic slag, rich in CaO and with some Al_2O_3 and FeO, from a remelting process at one of the Mansfielder works. In the druses here appeared tabular crystals (001) (100) with lengths parallel

[1]Under otherwise equal conditions, the size of crystals is a function of the quantity of the segregated mineral (see *Die Silikat-Schmelzlösungen*, II (1904), 164).

to the base of 49, 50, 51, and in one single crystal up to 56 mm., and of a thickness parallel to *c* of 13–14 mm. (Fig. 54). The slags contained about 90 per cent melilite. It may be noted that a melilite melt with some per cent of FeO is very thin.

In another slag, also containing melilite, rich in FeO (from Przibram, 1913), the lateral edge of the quadratic crystals measured 22 mm.

The largest crystals of *åkermanite*, found by me in a slag containing about 90 per cent crystallized mineral (with about 4 per cent Al_2O_3), occurred in thin tabular crystals (001) (100) with a little (110). They showed a length parallel to the base of 19, 21, and occasionally even 24 mm. and a thickness of 2–2.5 mm. In slags with 60–70 per cent åkermanite, the tabular breadth is commonly 5–10 mm.

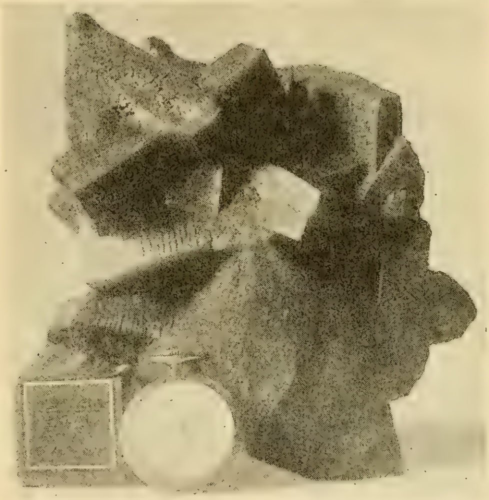

FIG. 54.—Large melilite crystals in slag. (Two-thirds natural size.)

My largest *fayalite* crystal (tabular along 010) shows a tabular size, 25×39 *mm*. In fayalite slags with 70–80 per cent fayalite, a tabular length of 25–30 mm is very common. Similar dimensions are also constantly met with in manganese-fayalite, $(Mn, Fe)_2SiO_4$.

Slags with only 40–50 per cent *olivine* $(Mg,R)_2SiO_4$, (where R = small quantities of Mn,Fe, etc.) show tabular crystals (on 010) about 7–14 mm. Smelting masses consisting of almost pure Mg_2SiO_4 I have not examined.

The freely developed crystals of *rhodonite*, $(Mn,Fe)SiO_3$ or $(Mn,Fe)\,SiO_3$, in the druses of slags with 65–80 per cent rhodonite, commonly show a length of 12–15 mm., sometimes up to 20 mm.

And the individuals of rhodonite in melts with about 80–95 per cent rhodonite may reach a length of 37–40 mm.

In a melt of 100 per cent $CaMgSiO_6$, diopside of a length ($\pm c$) of 30 mm. crystallized in the course of thirty-one minutes. This gives a rate of crystallization of *about* 1 *mm.* (*or* 0.97 *mm.*) *per minute.*

For the largest crystals of pseudowollastonite, melilite, åkermanite, fayalite (Fe_2SiO_4), manganese-fayalite [$(Mg,Fe)_2SiO_4$], and rhodonite [$(Mg,Fe)\ SiO_3$], commonly crystallized from solutions of 75, 80, or 90 per cent (or in one single case of even 100 per cent), we get a corresponding rate of crystallization, viz., about 1 mm. per minute. In fayalite, and almost certainly in manganese-fayalite, the rate is somewhat more than 1 mm. per minute, measuring the greatest length of the crystals.

All the minerals mentioned above that reach lengths of 20, 30, exceptionally even of 40 *or* 50 mm., crystallized (in the course of about half an hour) from very *thin fluid melts.* If, as a contrast to this, we take extremely viscous silicate melts as, e.g., $KAlSi_3O_8$, $NaAlSi_3O_8$, and SiO_2, there are formed, even if they are kept for one or more days just below the melting-point, crystals of only extremely small dimensions.

The *rate of crystallization,* no doubt, is a function of several factors, and one of the most important of these is the *degree of viscosity.*

All the foregoing minerals examined by me, which in the melted phase are very thin, are characterized by so great a *tendency to crystallization* that, from a solution of 80–100 per cent, they crystallize even under a very quick cooling. If, thus, we pour, e.g., melted $Fe_2\ SiO_4$, $(Fe,Mn)_2SiO_4$, $CaMgSi_2O_6$, or melted åkermanite into a calorimeter pipe, where the cooling from the melting temperature to usual room temperature requires only eight to ten minutes, and where the period of crystallization has a duration of only about one minute, we as a rule at least get some mineral segregated.

In very viscid molten masses it is quite different. To cause crystallization here, we must keep the molten mass heated just below the melting-point (or below the curve of crystallization) for

hours, days, or with extremely viscid masses, perhaps even for weeks.

This general fact has *inter alia* an important application to the *relation between the time of crystallization and the viscosity* in smelting masses of approximately *eutectic* composition. In the adjacent diagram (Fig. 55), *kl* indicates a certain viscosity and *mn* at lower temperature a higher degree of viscosity of the melt. When undercooling is not taken into consideration, the mineral *a* in a smelting mass of composition u_1 will begin to crystallize at t_1, in a

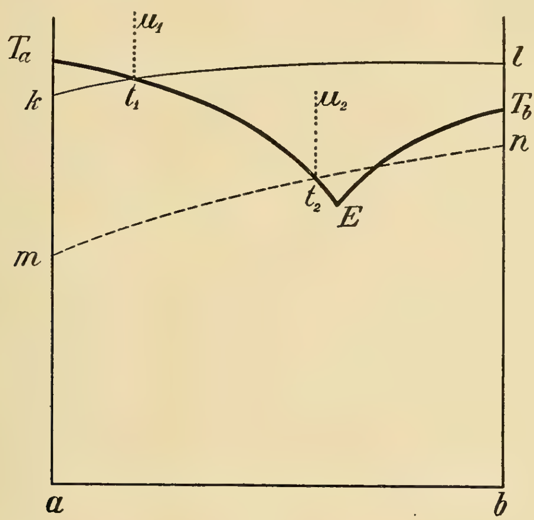

Fig. 55

smelting mass of composition u_2, on the other hand, at t_2—thus at a stage when the molten mass has grown more viscous. It is the same if in both cases we presume the same degree of undercooling. If the cooling proceeds at the same rate, we will get quite large crystals and some glass from the u_1 melt, while from the u_2 melt we will get glass with a small quantity of small crystals. At a still quicker rate of cooling, no crystallization at all takes place in u_2, so that it solidifies entirely as glass.

That crystallization actually takes place, as here theoretically explained, I have proved experimentally in my previous works.

In general, we may set up the thesis: *Compositions of eutectic or almost eutectic character further the formation of glass.* This principle really gives the general foundation for glass technology. At a medium rate of cooling of molten pure $CaSiO_3$, of pure Na_2SiO_3, or K_2SiO_3, respectively, crystallization takes place. A eutectic or nearly eutectic mixture of $CaSiO_3$ and Na_2SiO_3, respectively K_2SiO_3, gives, on the other hand, with fairly quick cooling, glass only, without any formation of crystals. If also, as in the manufacture of glass, a third component, SiO_2, is added, the viscosity is considerably increased even at high temperatures. On cooling a melt nearly of the composition of the ternary eutectic $CaSiO_3$: Na_2SiO_3:SiO_2 to a point on the melting surface (or in view of the supersaturation somewhat below the melting surface), the viscosity is so considerably increased that with medium quick cooling no formation of crystals can take place, i.e., glass results.

The principle here treated has a considerable influence on the structure of the geologically, relatively quickly cooled dikes and flows. By progressive crystallization at decreasing temperatures, the viscosity of the residue melt generally increases. The consequence is a fine-grained ground mass, or with still quicker cooling, a total restraint of crystallization, so that the remainder solidifies as glass. Melts rich in iron and basic (with about 50 per cent SiO_2) are not nearly so viscous as those poor in iron and acid (with about 68–75 per cent SiO_2). Because of this, glass basis usually plays a more important part in the quickly cooled acid rocks than in the basic.

Melts of anchi-eutectic composition poor in H_2O may be extremely viscous at the relatively low temperature of crystallization which characterizes them. With relatively quick cooling, consequently, the crystallization will be entirely or nearly entirely restrained. Thus it is no accidental circumstance that by far the most of *obsidians* have nearly the chemical composition of the granitic eutectic. Many, perhaps even the most, obsidians contain 72–76 per cent SiO_2 and between 0.3 Or:0.7 Ab+*An* and 0.5 Or:0.5 Ab+*An*. They thus even approach the "ternary" granitic eutectic, having an especially low temperature for the interval of crystallization, and thus also an especially high viscosity at the stage where

crystallization might take place. (See the chap. pp. 93–100 in my treatise on anchi-monomineralie and anchi-eutectic rocks, 1908.)

In *highly viscous* melts, inoculation causes no crystallization. Thus rhyolites contain glass mainly of the composition of quartz and feldspar, even though crystals both of quartz and feldspar have been segregated.

The entire lack of glass in deep-seated rocks is an evidence of quite extraordinarily *slow* cooling. The crucial point for the distinction between the deep-seated rocks, on the one hand, and the effusives and dikes on the other, is not pressure, but *time*. Many dikes have been solidified at very great depths, thus under the same pressure as the adjacent deep-seated rocks.

Granites of practically the same chemical composition show at times considerable variation in the size of grains. Thus the feldspar individuals in some granites have an average length of 0.3–0.5 cm., in others 1–1.5 cm. The relatively coarse grained granites form at more places much smaller areas (of, e.g., 10–50 $km.^2$) than those of finer grain (with areas of, e.g., 100–500 $km.^2$). The decisive point for the size of the grain thus can neither be duration of crystallization nor solidification in more or less great depth. The cause may, I suppose, be due to the fact that the magma of the relatively coarse grained granites had less viscosity on account of a higher content of H_2O, etc.

In this connection, it may be noted that the hypersthene-granite from Birkrem, etc. in the Ekersund District is medium fine grained, which may be due to the fact that the magma of this granite, as stated above,[1] contained relatively little H_2O. It might be interesting to examine whether all hypersthene-granites are characterized by only medium size of grains.

The extreme size of the grains of the pegmatite dikes of granite, augite- and nephelite-syenite, etc., proves, as maintained by many investigators, an extreme fluidity of the magma, depending on relatively large contents of H_2O, etc. At one atmosphere pressure the rate of crystallization of many minerals, by the segregation from *very thin* melts, is on an average 1 mm. per minute or 3 cm. per half hour, corresponding to about 1.4 m. per day (twenty-

[1] The *Journal of Geology*, XXX, 670..

four hours). Even though these figures cannot be transferred directly to pegmatite dikes formed under great pressure, it is evident, at any rate, that their crystallization did not necessarily require an exceptionally long time, speaking geologically. Granite-pegmatite dikes, commonly only 5, 10, 20 m., seldom as much as 50–100 m. thick, must have solidified in much shorter time than the rock in the large granite fields.

UNDERCOOLING (SUPERSATURATION)

The degree of supersaturation necessary to crystallization is a function of *time* and *viscosity*, and of other general factors. Furthermore there will perhaps also be involved a quality specific to each mineral.

For the melting of quite small quantities as, e.g., 10–20 gr. in platinum crucibles, the supersaturation necessary to crystallization is as a rule quite considerable. It is otherwise with fairly thin melts when we work with quantities of, e.g., 10–20 kg.

The explanation may probably be found in the fact that, after a certain degree of supersaturation in the first cooled peripheral parts (the surface or the walls of the crucible) diminutive crystals are formed, which in fairly thin melts abolish the supersaturation in the inner, somewhat more heated parts of the molten mass.

We shall illustrate this by an example (see *Die Sulfid-Silikatschmelzlösungen*, I (1919), 75) concerning the melting in graphite crucibles of different quantities of $(Ca,Mg)_4Si_3O_{10}$ (with 0.7 Ca:0.3 Mg) from which mainly åkermanite crystallized.

Two experiments were made, in one case with 19 kg., and in the other with 1.1 kg. The curve of melting (transition from solid to liquid phase) was found to give 1290° at the beginning and 1310° (or 1312°) at the end.

The curve of crystallization (transition from liquid to solid phase) gave (*a*) with 19 kg., period of crystallization twenty-five minutes, from 1310° to 1290°; (*b*) with 1.1 kg. period of crystallization six minutes, from 1280° to 1240°. The crystallization of the 19 kg. melt thus took place at the same temperature as the melting, i.e., *the crystallization took place without noticeable undercooling.* In the test with only

1.1 kg., on the other hand, there was found to be (by more parallel measurements) an undercooling of 30°–40°. In *very thin silicate melts* of sufficiently large quantity and with sufficiently slow cooling so that the crystallization lasts at least one or several hours, the crystallization, no doubt throughout, takes place with only an extremely small degree of undercooling. In *very viscous* melts, on the other hand, the undercooling may play an extraordinarily important part, even when very large molten masses are involved.

In normal striated deep-seated rocks I do not know of any structural element which indicates any traceable supersaturation. This must depend on the fact that they were cooled so slowly that the crystallization took place with quite insignificant supersaturation. To a certain degree it is otherwise with orbicular granite, diorite, etc., having concentric orbs. Here the successive shells from the center to the periphery (as I have shown in *Tscherm. Min. Petrogr. Mitt.*, XXV (1906), 396–403) may be explained under the supposition that the crystallization first began after some undercooling, especially along the eutectic boundary lines. This orbicular structure of the deep-seated rocks occurs as a rule only as a border phenomenon near adjacent older rocks, and this must be due to the fact that the cooling here took place somewhat quicker than in the central parts of the eruptive fields.

In the still more quickly cooled dikes and effusives, the supersaturation generally has played a certain rôle, as is indicated by partial resortion on account of supersaturation (see a following chapter). In very viscous dikes and effusives rich in silica, the supersaturation may have been of very considerable importance.

ON THE EQUILIBRIUM BETWEEN THE SOLID AND THE LIQUID PHASE OF MIX-CRYSTAL COMPONENTS

In *dikes* and *effusives*, the plagioclases, pyroxenes, etc., may show, as is well known, a zonal structure, and the "second generation" of the plagioclase has as a rule a different composition (a higher percentage of Ab) from the "first generation." This comes from *an absolutely lacking or a more or less incomplete equilibrium* between the segregated mix-crystals (or the first "embryonal" mix-crystals together

with the mix-crystals of the succeeding crystallization) and the corresponding components in the liquid phase.[1]

If we take plagioclase as an example, there will first crystallize from a magma with the plagioclase components in the proportion, e.g., 58 An:42 Ab—not only in melts consisting of pure An+Ab, but also in magmas with more or less of other components—[2] an embryonal mix-crystal with a composition about 84 An:16 Ab. The succeeding mix-crystals will contain gradually decreasing amounts of An and increasing amounts of Ab with absolutely lacking equilibrium say up to 30 An:70 Ab, and at last we may get thin zones with still less An and still more Ab. These last zones, as a rule, however, are in such small quantity that they may be entirely overlooked or may be seen only with difficulty under the microscope.

In order to decide if the equilibrium between the solid and the fluid phase is absolutely lacking or only more or less incomplete, we may start with a rock having an average proportion An:Ab, determined by the chemical analysis, and examine the composition of the "first" mix-crystal. For this purpose we may with some corrections, however, use the data given in my study on "Die physikalisch-chemischen Gesetze der Krystallisationsfolge in Eruptivgesteine,"[3] where I calculated from chemical analyses, the proportions of Or:Ab:An in many rocks (especially andesites), as well as the composition of the "first" phenocryst in the same rocks. I will give an extract from this table, recalculating Or:Ab:An to only Ab:An. The values following are the calculated quantities of An in the sum of Ab and An, both in the rock and the in phenocrysts. Further, I give the theoretical composition (or the An content) of the first plagioclase crystallizing in an Ab+An melt, according to the scheme delivered by Bowen (1913).

Percentage of An in Ab+An, (*a*) in the total rock, (*b*) in the phenocryst,[4] and (*c*) theoretically.

[1] I refer to the general explanation in *Die Silikat-Schmelzlösungen,* I and II (1903 and 1904), and to numerous later treatises by various authors.

[2] See this *Journal* for 1921, pp. 325, 327.

[3] Tscherm. Min. Petrogr. Mitt., XXIV (1905), pp. 503–4 and 512.

[4] The numbers refer to my table in 1905.

This review proves, in spite of the sources of error connected with the computation, especially of the first two rows of figures, that the "first" phenocrysts in the andesites, etc., here considered never contain quite as much An as the theoretical calculation requires. The phenocrysts indeed, in many cases, may be zonal; they may consequently contain in the kernel a little more An than the chemical analyses of the whole phenocrysts show. But even if we take this into consideration, the *kernel* of the phenocrysts will always or almost always contain not quite as much An as the theoretical calculation requires. That is to say, at the beginning of crystallization, as long as the phenocrysts were extremely small, the equilibrium between the solid and the fluid Ab+An phase was very incomplete, but not absolutely lacking. Under the microscope,

	Number							
	15	14	5	4	18	13	6	7
In the rock	42	43	42	46	32	37	47	42
In the phenocryst	69	68	62	62	56	56	60	57
Theoretically	76.5	76	76	78	70	73	78.5	76

we observe that the zonal structure of the plagioclases, as well as of the pyroxenes, etc., is in general more pronounced in the periphery than in the kernel of the individuals.

Concerning the dikes and flows, we may thus maintain as the crucial point that the equilibrium between the solid and the fluid mix-crystal phase was lacking to a very great extent. At the beginning of the crystallization, as long as the crystals were quite small, and at a stage with a relatively high temperature and consequently with a moderate viscosity of the magma, we may indeed assume a limited equilibrium. But at the later stages of the crystallization, viz., with larger crystals and at lower temperature and a higher degree of viscosity of the residual magma, only very incomplete equilibrium occurred.

As well known, we occasionally observe in the plagioclases of dikes and flows a *recurrence* of zonal structure. For example, around a series of zones, showing decreasing An, there may suddenly occur a zone with more An and less Ab. This probably depends

upon a downward sinking of the crystals.[1] If a zonal plagioclase sinks in a flow with more advanced crystallization in the upper than in the lower part, consequently, to where there is relatively more An than Ab, the new zone deposited on the crystal will contain relatively less Ab than the outer zone of the original crystal. Whether this explanation is right or not, may be decided by a study of plagioclases and other mix-crystals from the upper as well as from the lower part of the same flow.

Turning now to *deep-seated rocks:* the plagioclases, pyroxenes, etc., in most cases do not show zonal structure at all. This phenomenon is here exceptional, and even where shown the zonal structure and the chemical difference between the "first" and the "second" generations are not so prominent as in dikes and flows.

I thus found in looking over many thin sections of norites that only in a couple of cases did the outer zone of the hypersthene show a higher, though only a little higher, percentage of iron ($Fe\ SiO_3$) than the central part.

As to the plagioclases we will mention two cases: The extremely coarse-grained porphyritic labradorite-norite, with phenocrysts of labradorite up to 15–18 cm. long and 6–8 cm. broad, described in my treatise in *Quarterly Journal of the Geological Society* (1909), and mentioned in this *Journal* for 1921, page 439, shows the following proportion between An and Ab, the small quantity of Or not being taken into consideration.

In the rock as a whole (or in the magma)	58 An:42 Ab
In the phenocrysts	65 An:35 Ab
In the ground mass	55 An:45 Ab

In a magma with the plagioclase components in the proportion 58 An:42 Ab, the first crystallizing plagioclase, according to Bowen's scheme, must have the composition 84 An:16 Ab (Fig. 56).

During the entire first stage of crystallization, from $An_{84}\ Ab_{16}$ to $An_{65}\ Ab_{35}$, equilibrium between the solid and the liquid phase prevailed, i.e., the already segregated plagioclase at length transformed its composition. Then the equilibrium in the actual case ceased, probaby due to the fact that the crystals first segregated

[1] See my treatise in *Tscherm. Min. Petrogr. Mitt.*, XXIV (1905), 517, and the therein cited previous treatises.

had such considerable size as to impede the equalization of Ab:An in the solid and the liquid phase.

As another example we refer to the orbicular quartz-norite from Romsaas (described in this *Journal* for 1921, pages 430–35), the plagioclase, here also disregarding the small quantity of Or, of an average composition of An_1 Ab_1 (or An_{52} Ab_{48}), with the kernel of An_{58} Ab_{42} and the exterior of An_{45} Ab_{55}, locally even up to An_{38} Ab_{62}. This orbicular norite occurs in a quite small eruptive field

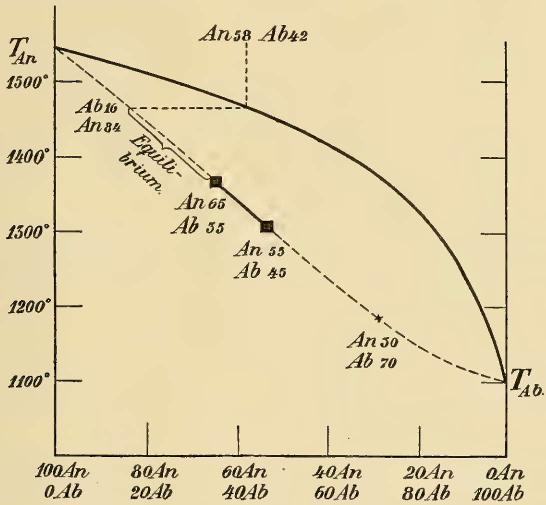

Fig. 56

close to the surrounding gneiss, which caused the time of cooling to be somewhat quicker than is common to deep-seated rocks.

Further I refer to the description given by V. M. Goldschmidt[1] of the "Trondhjemite" generally containing 69–76 per cent SiO_2, 16–13 per cent AlO_3, 3–1 per cent Fe_2O_3+FeO, 1–0.2 per cent MgO, 3.5–1.7 per cent CaO, 6.5–4.5 per cent Na_2O, 2.5–0.5 per cent K_2O, etc. The kernel of the plagioclase shows 20–32.5, most commonly 24–29 per cent An, and the outer zone about 16 per cent An, often with recurrence of basic and acid zones. That the zonal structure of the plagioclase of this rock is more pronounced

[1] Geologisch-petrographische Studien im Hochgebirge des südlichen Norwegens (Kristiania: Vidensk-Selskob, 1916).

than usual with the plagioclase of the deep-seated rocks may perhaps be due to the acid composition of the magma, which at a somewhat advanced stage of the crystallization may have been rather viscous.

The great difference in equilibrium between the solid and the fluid mix-crystal components, in dikes, and flows, with very incomplete, but as a rule not absolutely lacking equilibrium on one hand, and deep-seated rocks in some cases with medium, though mostly with practically complete equilibrium, on the other hand, must be due to the great difference of the *time* of the crystallization.

H. E. Boeke states in his *Grundlagen der phys.-chem. Petrographie* ([1915], p. 99) that: "Diese, eine Diffusion im festen Zustande erforderliche Änderung findet namentlich bei Silikaten nur mangelhaft statt." This is so far correct since this diffusion goes on much more slowly in silicates than in metals, but the diffusion in the silicates may become very extensive or even complete, when, as in many deep-seated rocks, there was sufficient time and the magma was rather thin fluid.

[*To be continued*]

REVIEWS

A Summer in Greenland. By A. C. SEWARD. Cambridge University Press, 1922. 8vo, pp. 100, pls. 47, maps 2.

This is a charming little book by a very capable student of ancient and modern plant life. The setting of the story is one of unique interest, present and past, physical and biological. The points of interest are many and are skilfully touched. Naturally they center where the author's competency is greatest, on the present and past plant life, especially as West Greenland is biologically the most unique of all Arctic regions.

The treatment of the present flora goes much beyond enumeration, classification, and similar formal and statistical matters, and touches upon adaptations, migrations, and relations that concern the life and death of plants in their battle with conditions that are inhospitable to the casual view, but which are not without their advantages to organisms that have succeeded in seizing upon these and using them.

The author's comparisons of arctic and of tropical modes of growth bring into vivid contrast the struggle for life when it is against adverse physical conditions, and the scarcely less severe struggle for life when it is against an overstress of biologic competition.

The author brings out sharply the great contrast between the development of plants in the Arctic and in the Antarctic regions respectively. The passage adds so much to the contrasts cited in the climatic paper on an earlier page of this number of the *Journal* that it is here quoted:

> Not a single flowering plant has been discovered within the Antarctic Circle. The most southerly representative of the flowering plants, over four hundred of which occur in Greenland, is a grass (*Deschampia antarctica*) which was found in the sub-Antarctic region and reaches its southern limit in lat. 62° S., a position corresponding to that of the Faroe Islands and the south of Finland in the northern hemisphere [pp. 71–72].

Other statements of the book are very opportune at this time when there is a disposition in certain quarters to discredit the conclusions reached long ago by Heer, Etheridge, and other early students, that strangely mild climates prevailed in the polar regions in certain geological periods, and the similar conclusions reached more recently on the basis

of new data by Nathorst, Schuchert, and others. Seward, whose standing and competency need no comment, makes it clear that he entertains no doubt about the reality of such warm climates in the regions he visited and in the ages he specifies. Some of his statements are not only worthy of quotation, but of emphasis:

The cliffs on some parts of the coast are built up of limestones, sandstones, shales, and old pebble beaches containing the remains of animals and plants characteristic of several geological periods and clearly indicating climatic conditions within the Arctic Circle much more genial than those at the present day. Even in the extreme north, on the shore of the Polar Sea, limestone rocks have been described by the Danish geologist, Koch, as veritable coral reefs of the Palaeozoic era.

The most northerly point at which fossil plants have been found is on the east coast of Greenland, between lat. 80° N. and 81° N. Fragmentary remains of plants were found by the Denmark Expedition of 1906–1908: these were described by the late Professor Nathorst, who recognized them as members of a flora which preceded that of our Coal Measures. The locality where these plants were found is nearer to the North Pole than any previously recorded for Carboniferous plants [p. 26].

The fossil-bearing rocks it was our aim to investigate are exposed along the shore and in the ravines of Disko and other islands and especially on the Nûgssuaq Peninsula. Most of them were deposited during the Cretaceous period; others are Tertiary in age. Slabs of rock detached with the aid of a pick-axe from the side of a ravine where the hills are made of a succession of sheets of sediment—the sands and muds of some ancient lake or lagoon—are found to be covered with the clearly outlined impressions of large leaves like those of the Plane or Tulip tree, fronds of ferns hardly distinguishable from species (of the genus *Gleichenia*) living to-day in tropical and sub-tropical countries; there are also twigs of Conifers, some of which are almost identical with those of the Mammoth tree (*Sequoia* (*Wellingtonia*) *gigantea* now confined to a narrow strip of the Californian coast), and massive stems of forest trees. None of the leaves preserved in the Greenland rocks have a greater fascination for the student of the past history of living plants than those of the genus *Ginkgo*. This genus is now represented by a single species, the Maidenhair tree (*Ginkgo biloba*), which is sometimes said to occur in a wild state in China, though it is probable that even in China and Japan, where it grows abundantly, it is only as a cultivated tree associated in the oriental mind with some religious symbolism. *Ginkgo* is often planted in gardens and parks in Europe and America and is distinguished from all other trees by its broad and often lobed, wedge-shaped leaves. Fossil leaves, some indistinguishable from those of the sole survivor of this ancient genus, have been found in the Cretaceous sediments on Upernavik Island (Map *B*), in sedimentary rocks associated with basaltic lavas at Sabine Island (lat. 75° N.) on the east coast of Greenland, at several

localities within the Arctic Circle, also in many other regions of both the Old and the New World. These records afford an exceptionally striking illustration of the possibilities offered by a study of the herbaria of the rocks of connecting the present with the past, of following the wanderings over the world and of tracing the rise and fall in their fortunes of still living members of the plant kingdom. These fragmentary relics, "The ghostly language of the ancient earth," suggest problems that are more easily stated than solved.

Many records of ancient floras are readily decipherable, foliage shoots and clearly outlined leaves showing the finest veins, the plant substance changed into a thin film of coaly substance which on treatment with certain chemicals reveals under the microscope details of the surface cells and throws light both on the affinities of the plants and on their relation to the world in which they lived. The minute structural details of petrified wood after it has been cut into transparent sections can be examined with as much thoroughness as those of a living stem; the living substance has gone, but the framework remains and through it we obtain an insight into the mechanism of the plant which was alive some millions of years ago. Other fossils are but "age-dimmed tablets traced in doubtful writ," and these add zest to the task of interpretation [pp. 27–29].

One of the most convincing and impressive arguments in support of the prevalence of an almost, if not quite, tropical climate in Greenland during the Cretaceous epoch is furnished by portions of large leaves and pieces of the fruit of a Breadfruit tree discovered by members of a Swedish expedition in 1883 on the coast of Disko Island and described by the late Professor Nathorst, who was well known as an Arctic explorer and an exceptionally able student of the floras of the past. The Breadfruit, *Artocarpus incisa*, which the Greenland fossil closely resembles, is cultivated practically all over the tropics and is native in some of the Pacific Islands [p. 31].

The little book is full of charming pictures, literary as well as photographic, and it is studded all through with substantial things well worth knowing.

T. C. C.

Geomorphology of New Zealand, Part I, Systematic. By C. A. Cotton. Wellington, N.Z.: Dominion Museum, 1922. Pp. x+462, pls. 1, figs. 442.

One of the beauties of the science of geology is the wide applicability of its underlying principles. A generalization is developed in one country where conditions or methods of study are particularly favorable, then later it is used by geologists in far distant countries to solve problems hitherto obscure. Thus its validity becomes more firmly established. The chief interest to American geologists in this work by Professor

Cotton is the success with which he applies certain of Davis' principles of physiography to the interpretation of New Zealand land forms. His aims are well stated in the following sentence from the Preface:

In the hope of setting forth these principles in a convincing manner and thus popularizing in New Zealand the fascinating study of land forms, the present work (Part 1) is cast in the form of a textbook of geomorphology for New Zealand students and general readers.

In pursuance of this plan, the history of the science of geomorphology is traced from its beginning early in the nineteenth century to the present time. In this development, the work of American geologists has been given a very important place. Following Davis, the distinction is drawn between the empirical and explanatory methods of description of land forms, and the great superiority of the explanatory method is set forth.

The central theme around which the subject-matter is arranged is the concept of the erosion cycle. Several chapters are devoted to the normal erosion cycle, and each stage is illustrated by New Zealand examples, many of them from the author's own work. Complications in the normal cycle claim a share of attention, as does also the arid cycle. A comparatively recent extension of the principle of the erosion cycle is its application to glacial action. As glaciation is a notable feature in New Zealand, it naturally receives rather full treatment. Briefer treatment is accorded to volcanoes and igneous activity, which are considered as interruptions of the normal cycle. There is no lack of igneous phenomena in New Zealand and some excellent illustrative material is here incorporated. The closing chapters deal with the work of waves and the development of coastal outlines.

The organization of material is admirable. The numerous illustrations are in most cases very effective, especially the line drawings. These, together with the writer's lucid and interesting style, make the book very attractive. It should make a valuable addition to any geological library and merits considerable attention from students of physiography in countries other than the one about which it is written.

A. H. B.

Silver Enrichment in the San Juan Mountains, Colorado. By Edson S. Bastin. Bulletin 735-D, United States Geological Survey, Washington, D.C., 1922. Pp. 67, figs. 18.

The paper presents primarily some details of silver enrichment in the San Juan Mountains as shown by a study of polished ore specimens. It was not possible for the writer himself to consider exhaustively the

field relations; for facts about these, therefore, reliance was placed largely on the observations of earlier workers in the area.

Typical ore specimens from ten mines of the region near Ouray and Telluride are first described. With the co-operation of Mr. Chase Palmer, a chemical study of the hot springs near Ouray was made, but the neutral waters are high in calcium sulphate and yielded no final conclusions as to their origin.

At several mines it is found that pearceite is a *late* primary mineral, suggesting that in this form the metal has greater solubility than other silver salts found in these ores. A new silver mineral, apparently intermediate between argentite and galena, is noted in several specimens, separating primary galena from secondary argentite. In some of the mines in the Red Mountain district between Ouray and Telluride, replacement results in a gradual substitution of silver and copper for lead, zinc, and iron—a change roughly comparable to the position in the electromotive series of the metals concerned.

In general, these studies seem to show that silver sulpho-salts are important in both primary (hypogene) and secondary (supergene) mineralization. Apparently the sulpharsenides and sulphantimonides of silver tend to be among the later generations of primary minerals. Both downward silver enrichment and the upward transportation of silver minerals take place more readily in neutral or but faintly acid waters. The facts given also illustrate beautifully the importance of relief and erosion in stripping off the enriched zone, as well as the effect of rising solutions, especially those rich in hydrogen sulphide, in retarding the downward progress of enrichment.

More than anything else, however, the facts so well presented illustrate the growing importance of micropetrography of the ores in solving economic problems. To quote the writer:

> The judgment as to the probable success of deep mining in veins rich in silver near the surface should not be prejudiced by preconceived ideas of the importance of enrichment. Each district and in some districts each mine presents a special problem. The method of microscopic study of the ores worked out in recent years offers a method of determining, roughly at least, the relative importance of primary and secondary processes in the deposition of silver ores far in advance of the ultimate test by actual development. The practical value of information of this sort is out of all proportion to the moderate cost at which it may be procured.

Occasionally the reviewer is led to doubt the evidence adduced to prove the secondary character of certain minerals. Thus:

The pyrargyrite and proustite of the ores were apparently deposited after the primary ore had been somewhat fractured. They were not observed intergrown contemporaneously with any of the undoubtedly primary ore minerals. In view of this fact and their apparent playing out with depth, they are regarded as products of downward enrichment.

To the reviewer, it seems that this sort of evidence is rather unsatisfactory as a guide in developing a mine, since the same distribution and lack of intergrowth of the two silver minerals might well be attributed to their irregular deposition from *late* hypogene solutions.

But such minor points are almost negligible. The paper is well illustrated with camera lucida drawings. It is a very real contribution to applied economic geology, and it is to be hoped that the writer will continue with his fruitful studies of silver enrichment.

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Geologie von Mexiko. BY WILHELM FREUDENBURG. Gebrüder Borntraeger, Berlin, 1921. Pp. viii+232, pls. 2, figs. 29, tables.

This publication is a digest of the existing literature on Mexican geology and as such it fills a distinct need. Under section 1, "Summary of Morphology," the author treats of boundaries, coasts, areal extent, orographic elements, vulcanism, and faulting. He then describes in turn the seven physiographic provinces of Mexico and their history, following Warren N. Thayer.

Section 2, which is headed "Stratigraphy and Kinds of Mountains," constitutes nearly half of the volume. Beginning with the Archean, the formations are given brief descriptions and the geologic history interpreted as far as possible from existing knowledge. Considerable prominence is given to the Mesozoic, particularly the Jurassic and Cretaceous. Typical Mexican stratigraphic successions (including also the fossils) are correlated with the European time scale in several diagrammatic sections.

The subject of vulcanism fills most of the remainder of the volume. It is noteworthy that while Tertiary and Quaternary effusives surface a considerable fraction of the whole area of Mexico, the post-Cambrian intrusives are comparatively insignificant. "The Active and Extinct Volcanoes of Mexico"; "Relation of the Tertiary Vulcanism to the Structure"; and "Relations between Volcanoes and Earthquakes" are the subjects of the next three sections, and attest the fact of the great importance of vulcanism in the recent geologic history of Mexico. The mineral deposits of Mexico are given as much space as could be expected in a

brief general treatise. The fairly extensive bibliography of Mexican geology will be of value to many.

A. H. B.

Nomenclature and Description of the Geological Formations of Indiana. By E. R. Cumings. *Part IV, Handbook of Indiana Geology.* Publication 21, The Department of Conservation, State of Indiana, 1922.

This report is one of the six papers brought together in Professor Logan's admirable handbook of Indiana Geology. Professor Cumings' reputation as a stratigraphic paleontologist will lead the experienced geological reader to expect a thorough piece of work in this section and he will not be disappointed. The bibliography dealing with the stratigraphy and fossils of the state, which is an important feature of the work, occupies thirty-six pages. Professor Cumings' intimate knowledge of the fossil faunas of Indiana has enabled him to carry out the formidable task of critically reviewing and summarizing the most pertinent data in the several hundred papers represented in this extensive literature in an admirable manner. His detailed tracing of the history of each of the fifty-eight formation names establishes a sound basis for a stable nomenclature. This careful review of the Indiana formational nomenclature will be of much value to the geologists of adjacent states as well as to those of Indiana. Geologists concerned with the nomenclature of geologic formations may be interested in Professor Cumings' proposal regarding the substitution of Medinan for Oswegan. Professor Cumings draws the Ordovician-Silurian boundary at the top at the Richmond instead of at the bottom, where some paleontologists have proposed placing it in recent years.

The well-planned geologic time scale summarizes, so far as this is possible on a single sheet, the present state of knowledge of the stratigraphy of the state. This important illustration should have had a general title printed on it.

A map showing type localities of geological formations in the Central States and Southern Ontario is a useful feature of the report. It indicates, however, only a small portion of the type localities in this extensive region. A series of geologic sections across Indiana and eight paleogeographic maps illustrate the broader geological features of the state and its past geological history, as interpreted by the author.

The historical and bibliographic features of this paper will make it an indispensable work of reference for stratigraphic paleontologists.

E. M. Kindle

Stratigraphy of the Pennsylvanian Formations of North-Central Texas. By F. B. PLUMMER and R. C. MOORE. University of Texas Bulletin 2132, 1921. Pp. 237, pls. 27, figs. 19.

This work is an important contribution to the literature of American stratigraphy. Its publication was made possible through the officers of the Roxana Petroleum Corporation who were generous and far-sighted enough to recognize that the benefits to science resulting from the presentation of these facts to the geological profession outweigh any possible detriment to their own interests.

The Pennsylvanian rocks of north-central Texas occur as two great inliers which occupy about 7,000 square miles. Because of their isolation from the classic Mississippi Valley section their study has been long delayed, the only earlier publications dealing essentially with their stratigraphy having been written by Tarr, Cummins, and Drake in the early volumes of the Geological Survey of Texas. Recently the discovery of the great petroleum resources of the region has stimulated geologic investigation.

The Pennsylvanian sedimentation in northern Texas began with the deposition of the petroliferous limestone and carbonaceous shale of the Bend group. At the end of this first epoch there was an uplift with folding which resulted in erosion. Then followed thick beds of sand and gravel interbedded with clay making up the Strawn group. These coarse sediments were succeeded largely by the calcareous oozes and marls of the Canyon group. During the latter part of the period there was a long epoch of oscillating levels of the sea during which beds of clay, sand, and limestone were deposited in alternating succession forming the Cisco group.

Of especial interest are the authors' conclusions with regard to the Bend group. On account of its economic importance as a source of petroleum it has received much attention in the past, and its age has been a matter of dispute. The name Bend was proposed for the black shale and limestones which overlie the Ordovician beds at McAnnelly's bend of the Colorado River in San Saba County. Although resting unconformably beneath the coal-bearing Carboniferous sandstones, they contain a preponderance of Coal Measures fossils, and were therefore thought to belong to the Pennsylvanian. These beds were first referred by Tarr to the Mississippian, then as a result of Cummins' work, they were transferred to the Pennsylvanian system. The lowest member, previously known as the Lower Bend shale, is here named the Barnett shale. Many of its fossils are closely related to the Upper Mississippian

forms, while some indicate a possible Pennsylvanian age. From the standpoint of stratigraphic relations the Barnett shale seems to be inseparable from the beds which overlie it. The conclusion of the authors is that the Barnett shale is probably Pennsylvanian, and may be correlated with the lower part of the Morrow group of northern Arkansas and northeastern Oklahoma. The Marble Falls limestone, the middle member of the Bend group, has a fauna similar to that of the Morrow group. It may be correlated also with the Wapanucka limestone of southern Oklahoma. It is certainly older than any of the Pennsylvanian divisions which have been described in the northern Mid-Continent region. The Smithwick shale, the upper member of the Bend group, contains a fauna of which a very important element is confined, as far as is known at present, to this formation. All of the associations of this fauna appear to be with the Pennsylvanian, although the occurrence of such a form as *Bembexia nodomarginata* is an interesting remnant of Mississippian aspect.

A. H. B.

Fauna from the Eocene of Washington. By Charles E. Weaver and Katherine Van Winkle Palmer. University of Washington Publications in Geology, Vol. I, No. 3, pp. 1–56, pls. VIII–XII, June, 1922.

This, the third of the series of geological publications of the University of Washington, is a decided improvement upon the two preceding numbers and appears, on the whole, to be equal to the best of the many papers which have appeared on the West Coast Eocene. The authors describe the University of Washington collecting stations from 315 to 370; describe one new genus, *Phaenomya,* of freshwater Pelecypoda; and describe fifty-six new species and four new subspecies of mollusks. (Not 64 new species as stated on page one.)

Although the paper has fewer errors than many which have appeared of late years on the paleontology of Western Eocene, there are some points open to criticism, the most important of which, it is hoped, the authors will correct in the "Stratigraphical and Faunal History of Northwest Eocene" to be published later. It is not clear why the first two papers of the series had continuous pagination and plate numbers while this one goes back to page one, but does not interrupt the plate series. Six years have elapsed since the appearance of the first number of the series of publications; at this rate therefore an index to Volume I may not be expected for several more years; in the meantime an alphabetical

arrangement of the species would have been much more convenient to the user than the systematic arrangement which was adopted. It is necessary now for each student to prepare his own index or hunt laboriously for any species which he may wish to consult.

The unqualified use of subgenera in place of genera may have some points of advantage, but the plan is open to severe criticism on the ground of the enormous bibliographical difficulties involved; it would seem that whatever system or method is used, an author should at least be consistent in the same paper. The authors here describe *Epitonium* (*Boreoscala*) *washingtonensis*, new species, and figure it as *Epitonium washingtonensis* leaving out the subgenus; but they describe *Pyramidella* (*Syrnola*) *vaderensis*, new species, and figure it as *Syrnola vaderensis*, leaving out the genus; etc.

The authors have failed to designate type specimens of their new species, and do not state where the described and figured specimens are located although such has been accepted museum practice for many years. The original collection was divided into two parts, one of which was taken to Cornell University for study, but the reader is left entirely in the dark as to where the actual specimens described and figured may be consulted. This is a matter of great importance because many of the descriptions contain no comparisons with other species.

The illustrations are from photographs and are much better than any which have previously appeared in this series of the University publications. *Nerita washingtoniana* (Pl. XI, fig. 4.), however, is represented by a mere blotch of light while the description is so generalized that it is entirely unrecognizable.

The authors have tangled the nomenclature of two freshwater gastropods to an unpardonable degree. On page 44, *Goniobasis hannibali*, new species, is described as "extremely variable." The extreme form in sculpture has been taken for the type of the species. *Goniobasis olequahensis* (Arnold and Hannibal) represents the smooth type of shell. . . . . The collection contains specimens which show transition stages between the two types of shell. . . . . One must then wonder why the "new species" was described at all. They state that Dr. H. A. Pilsbry has determined *Ambloxis olequahensis* Arnold and Hannibal to be a *Goniobasis*, yet on the same page (45) they describe *Goniobasis olequahensis* new species! If new, why was not another name chosen?

It is noted that the measurements published in the descriptions are far from being in agreement with the statements given in the explanations of the plates in some cases, as for instance, *Lima packardi* (p. 15).

The continued repetition of certain specific names in different genera, is of course acceptable under the rules of nomenclature, but it is exceedingly troublesome to those who are obliged to use the publications; it often happens that subsequent authors transfer species from one genus to another without cross references and difficulties are multiplied enormously. The specific names, *washingtonensis*, *washingtoniana*, *cowlitzensis*, *olequahensis*, and *vaderensis* have been used over and over again in Washington paleontology, and it is with regret that we notice the present authors have added to this assemblage.

Several typographical errors have been noted but the only one seen which is likely to give trouble is on page 34, where *Turritella washingtoniana* is referred to Plate XI, figures 13, 14, 16. The plate number should read XII.

G. Dallas Hanna

The Story of the North Star State. By D. E. Willard. St. Paul, Minnesota: Webb Publishing Company. Pp. 395, Figs. 156.

This work belongs to a new and increasingly important class of geologic literature, whose avowed purpose is to present scientific facts and principles in such simple language that the intelligent general reader may assimilate them. That the author has succeeded admirably in carrying out his aim is the belief of the present reviewer. The geologic history of Minnesota, particularly that of glacial and post-glacial times, has been made into an interesting story without any loss of scientific accuracy.

A. H. B.

Abrégé de Géographie physique. By Emmanuel de Martonne. Paris: Librairie Armand Colin, 103 boul. St. Michel, 1922. Pp. ii+356, pls. 8, figs. 100.

As its name implies, this is an abridgment of a larger work by the same author, namely his *Traité de Géographie physique* (1st edition 1909, 3d edition 1920). Designed primarily as a textbook, it is addressed to the general reader as well as to the student. The plan of outline is the same as that of the *Traité* but the method of presentation is in general different. Brevity has been secured by leaving out as far as possible concrete examples illustrating the general laws. Not wishing to treat all the questions summarily, the author has chosen the most important or the simplest, setting them forth in a manner as complete as the limited space permitted.

Each of the four parts (Climate, Hydrography, Relief of the Land, Biogeography) is followed first by a list of references furnishing the teacher with the elements for a more detailed study, then by practical exercises designed to verify in the field the newly acquired principles. An entirely new chapter treats of the relations of human geography with physical geography.

In English speaking countries, the class to which the *Abrégé* will appeal chiefly will undoubtedly be teachers of geography. Combining as it does a clear and precise method of presentation with up-to-date scientific accuracy, it constitutes an excellent introduction to the study of physical geography for anyone who reads French.

A. H. B.

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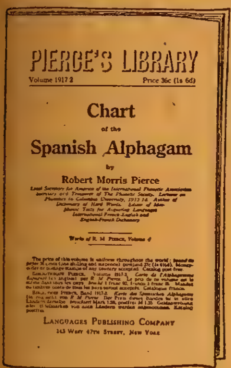

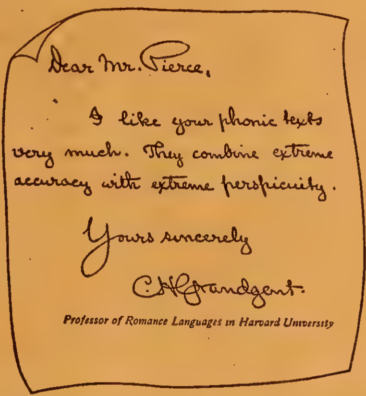

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Yours sincerely

C. H. Grandgent.

Professor of Romance Languages in Harvard University

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Among articles to appear in early numbers of the *Journal of Geology* are the following:

Significant Ameliorations of Present Arctic Climates. By T. C. CHAMBERLIN.

The Physical Chemistry of the Crystallization and Magmatic Differentiation of Igneous Rocks. VIII. By J. H. L. VOGT.

The Mineralography of the Feldspars. Part II (Concluded) By HAROLD L. ALLING.

The Temporary Mississippi River. By WALTER H. SCHOEWE.

Summary of the Geology of the Beartooth Mountains, Montana. By ARTHUR BEVAN.

Was there Pennsylvanian-Permian Glaciation in the Arbuckle and Wichita Mountains of Oklahoma? By SAMUEL WEIDMAN.

VOLUME XXXI NUMBER 4

THE JOURNAL OF GEOLOGY

May-June 1923

THE DIFFERENTIATION OF THE DRIFT SHEETS OF NORTHWESTERN ILLINOIS

MORRIS M. LEIGHTON
Illinois Geological Survey, Urbana, Illinois

THE PROBLEM

Ever since the present classification of the Pleistocene has been evolved with its five glacial stages—the Nebraskan, Kansan, Illinoian, Iowan, and Wisconsin—the drift of northwestern Illinois, west of the mapped Wisconsin, has had an uncertain status. After the important discovery of the Illinoian stage of glaciation, about three decades ago, Mr. Leverett referred the outermost drift in northwestern Illinois tentatively to the Illinoian stage of glaciation, and the next inner drift to the Iowan.[1] Subsequently the existence of an Iowan drift in the Labrador field was ignored by Mr. Leverett in at least two publications, and its existence in the Keewatin field questioned.[2] In 1908, Dr. William C. Alden carried on studies along Rock River and to the west, and reached the conclu-

[1] Frank Leverett, "The Illinois Glacial Lobe," *U.S. Geological Survey Monograph XXXVIII* (1899), Plates VI and XII.

[2] "Weathering and Erosion as Time Measures," *American Journal of Science*, Vol. XXVII (1909), p. 351, and "Comparison of North American and European Glacial Drift Sheets, *Zeit. für Gletsch.*, Book 4 (1910), p. 248.

sion that no post-Illinoian ice sheet had invaded the territory.[1] It should be noted, however, that the area which he studied lies mainly west of that which the present author has called the Belvidere lobe. In 1913, Leverett suggested that the drift of northwestern Illinois and certain other drift in western Wisconsin and southeastern Minnesota may be a late stage of the Illinoian and a correlative of the Iowan drift in Iowa. Accordingly the name "Late Illinoian or Iowan" was proposed for such drift.[2] More recently the question was raised as to whether some of the drift south of Belvidere and east of Dixon may be the product of a greater advance of the Early Wisconsin ice than had formerly been suspected.[3] Because of this uncertain status, the drift of northwestern Illinois, particularly with reference to its age, has been the first to be restudied by the Illinois Geological Survey in its program for the re-examination of the Pleistocene of the state.

Throughout the investigation, the questions which were kept in mind were: (1) Is there but one drift sheet or more than one in northern Illinois, west of the mapped Wisconsin moraine? (2) What is the age of the drift or drifts?

MODE OF ATTACK

Information for answering these questions was sought in a careful study of the topographic expression of the drift, the composition of the drift, the stratigraphic sequence of the Pleistocene materials, the state of weathering of these materials, and the drainage changes which have occurred.

Heretofore in the gathering of Pleistocene data in this area, reliance has been placed chiefly on road cuts, railroad cuts, and stream exposures, but they are comparatively few and the data derived from these must be used with great discretion. The major-

[1] William C. Alden, "Concerning Certain Criteria for the Discrimination of the Age of Glacial Drift Sheets as Modified by Topographic Situation and Drainage Relations," *Journal of Geology*, Vol. XVII (1909), p. 695. Somewhat further data was included by Dr. Alden in "The Quaternary Geology of Southeastern Wisconsin," *U.S. Geological Survey, Prof. Paper 106* (1918), pp. 137–60. Most of the succeeding authors have followed Alden's mapping, p. 153.

[2] "Iowan drift" (abstract), *Bulletin of the Geological Society of America*, Vol. XXIV, (1923), p. 698.

[3] *U.S. Geological Survey, Prof. Paper 106* (1918), p. 153, referring to the question raised by Leverett.

ity of these exposures occur on slopes where slopewash and deposition make their value debatable and uncertain. Many of the road cuts are also too shallow to show what is vital. It was the working principle of the present study to accept only such data in regard to depth of weathering as could be obtained on the uplands, where there is a minimum of wash, and to secure enough data, if possible, to carry conviction. In addition to examining all known exposures, borings were made with a sectional auger, $1\frac{1}{4}$ inches in diameter, to depths ranging from 2 feet to $17\frac{1}{2}$ feet. More than 500 such borings were made. The work required somewhat more than two field seasons with the aid of an assistant and an automobile. The distribution of the borings and exposures, which serve as a part of the basis of this paper, is shown in Figure 1.

GENERAL CONCLUSIONS

As a result of the studies made the following conclusions were reached.

1. There are at least two distinct drift sheets in northwestern Illinois, west of the Marengo Ridge and north and west of the Bloomington moraine. The uppermost drift in southern Boone, northern DeKalb, eastern Ogle, and southeastern Winnebago counties was deposited at a much later time than the drift in the area to the west. This area (see Fig. 2) has been called the Belvidere lobe after the town of Belvidere, immediately south of which the drift is well displayed.

2. The drift west of the Belvidere lobe is truly Illinoian in age, while that of the Belvidere area is Early Wisconsin in age. The boundary between the two is radically different from the old Iowan-Illinoian boundary.

3. A post-Illinoian ice sheet invaded the Green River basin, approximately to Rock Island County, depositing a thin drift which was subsequently largely buried by the outwash from the Early Wisconsin ice during the building of the Bloomington moraine and by the Rock River Valley train of Late Wisconsin age. The evidence is insufficient to determine whether this ice lobe, now called the Green River lobe, is Iowan in age or a correlative of the Shelbyville drift of Early Wisconsin age.

FIG. 1.—Skeletal map of northwestern Illinois showing the distribution of the borings and significant exposures involved in the present study. Scale, $1''$ = approximately 30 miles.

4. The gorge of the Mississippi River below Cordova seems referable in time to the invasion of the Green River lobe, and the gorge of the Kishwaukee River and the youthful gorge of the Rock River, extending from just below the debouchure of the Kishwaukee to Byron, is referable to the invasion of the Belvidere lobe. The rest

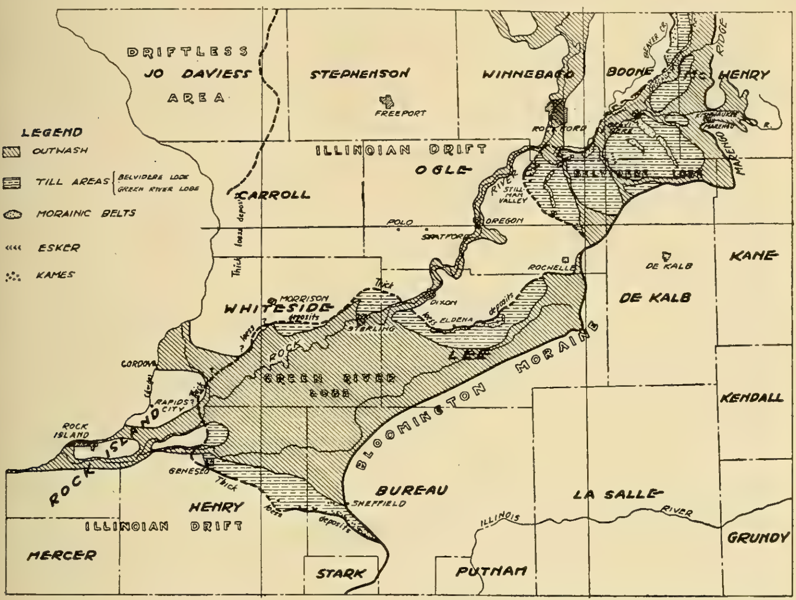

FIG. 2.—Glacial map of northwestern Illinois, showing the drift sheets and outwash deposits outside of the Bloomington moraine and the Marengo Ridge. The broken boundary lines indicate indefiniteness. Scale, 1″ = approximately 30 miles.

of the Rock River Valley, below Byron, is Illinoian and post-Illinoian in development.

A more complete account of the evidence for these conclusions will be published in a report by the Illinois Geological Survey, but it was deemed of sufficient scientific interest to give the main lines of evidence and interpretations in the present paper.

ACKNOWLEDGMENTS

The writer was greatly favored and helped by field conferences, one at the close of each of the first two seasons, by the late Professor R. D. Salisbury, of the University of Chicago, and F. W. DeWolf, Chief of the Illinois Geological Survey. Grateful acknowledg-

ment is hereby recorded. The writer also wishes to express his appreciation of the distinct service rendered by his assistants, Dr. E. P. Rothrock, of the University of South Dakota, and Messrs. George E. Ekblaw and C. P. Halushka, students at the University of Illinois.

THE BELVIDERE LOBE

Extent.—The Belvidere lobe extends as far west as Stillman Valley, Ogle County, within 4 miles of the present course of Rock River (see Fig. 2). It includes only a part of the territory which was mapped Iowan in *United States Geological Survey Monograph XXXVIII*, and its boundary transects the old Iowan area, and excludes the drumlinoid forms of northwestern Boone County which are regarded as Illinoian in age.

The ice built a curving moraine which may be traced from a point 1½ miles south of Holcomb to a point 1½ miles west of Davis Junction and thence northeast to the forks of Kishwaukee River. Some kames enter into its constitution and increase its morainal aspect. Beyond this moraine, the occurrence of relatively fresh drift, as revealed by auger borings, relatively fresh gravels as north of Stillman Valley, a smoothed aspect of the topography, and the narrow gorge of the Rock River just beyond the isolated hill at the mouth of the Kishwaukee River, indicate that the ice reached its limit some 4 miles at a maximum beyond this moraine without leaving such marginal accumulations as might be called a moraine. West and north of Belvidere and northeast of Capron there are thickened marginal deposits, but elsewhere they are poorly developed or entirely lacking. No valley trains have been identified; whether there were none originally or whether they have been buried by the alluvial back-water fill from the Late Wisconsin Valley train of Rock River and Kishwaukee River cannot be determined. Back within the area there are some well-developed knolls and ridges of fresh aspect, made up of both till and gravel. The drift is thick enough over some areas to control the major features of the topography, but near the margin the old land surface is incompletely masked. Probably the average thickness does not exceed 15 or 20 feet.

Significant phenomena.—Within the limits of the Belvidere lobe the drainage lines are poorly developed, the surface is undulating and considerable portions have a decidedly glacial aspect; the loess is thin, many crystallines and a few limestone bowlders occur on the surface, the drift materials show moderate oxidation and are leached to a shallow depth. An average of 120 borings showed 2.1 feet of soil and loess-like silt over 1.9 feet of leached till with calcareous till below, making a total of 4.0 feet of leached material (see Table I). One suggestive case of superposed tills occurs ½ mile

TABLE I

SUMMARY OF THE DATA ON LEACHING

Areas	Soil	Loess-like Silt	Till	Total Average*
Bloomington drift (56 borings)......	1.1′	1.5′	1.1′	3.7′
Belvidere lobe (120 borings)........	0.9′	1.2′	1.9′	4.0′
Green River lobe (119 borings)......	1.2′	3.2′	1.3′	5.7′
Iowan drift in Iowa (146 borings)....	1.2′	0.5′	3.5′	5.2′
Illinoian drift (150 borings).........	0.9′	3.0′	4.2′	8.1′

* Of the 120 borings in the Belvidere lobe, less than 6 per cent did not pass through the leached zone; and of the 119 borings made in the Green River lobe, 4.2 per cent did not; of the 146 borings made in the Iowan drift area of Iowa, 10 per cent did not; and of the 150 borings made in the Illinoian area, 23 per cent did not.

Of the borings in the Illinoian area which showed 5 feet or less of leaching, 74 per cent occur in the headwater region of northeastern Boone County and in the Kyte River basin of Ogle County where the dissection is slight and the ground-water table high.

northwest of Irene station, where the Illinois Central Railroad cuts through the upland. Here two glacial tills are separated by fossiliferous loess and fossiliferous silts and sands with some suggestion of old vegetation, but neither the fossil content nor the vegetation excludes the possibility of a retreat and readvance of the same ice-sheet. This exposure was also observed and recorded by Leverett.[1] At or near the margin of the lobe some drainage changes occurred. The two most important ones were the diversion of the Rock River from its old course past Stillman Valley to the present gorges upstream from Byron, and the translocation of the Kishwaukee from its old course at Harrisville to the gorge across the divide east of New Milford. Two others having a bearing on the direction of ice movement will be mentioned later.

[1] *U.S. Geological Survey Monograph XXXVIII* (1898), p. 138.

Comparison with the Illinoian area to the west.—The features of the Illinoian area to the west, taken as a whole, are in considerable contrast to those just mentioned for the Belvidere lobe. The erosional topography west of Rock River is largely an inheritance of preglacial erosion, but locally there are morainic belts and post-glacial gorges whose degree of erosion appears greater than that of the Belvidere lobe. The oxidation of the drift beyond the Belvidere lobe is stronger than that of the Belvidere drift, the color ranging from brown to rusty brown; the till is more compact and the upper part has a greater concentration of residual pebbles; the mantle of loess is thicker; the loess rests on the till unconformably, that is to say, the till beneath the calcareous and fossiliferous loess is oxidized and leached, whereas in the few instances in the Belvidere lobe where calcareous loess was penetrated by the auger it was found to rest on calcareous till containing limestone pebbles; gumbotil was found in a score of places in the Illinoian area, whereas no occurrence of this distinctive material is known in the Belvidere lobe except possibly at two points where the auger penetrated a gumbo-like till after passing through relatively fresh drift. (See Fig. 1 for the distribution of the exposures and borings which show this and other significant data.) Another very characteristic phenomenon of the extra-Belvidere drift is the occurrence of an old loess-like clay, $1\frac{1}{2}$ to 4 feet thick, which is non-calcareous, compacted, oxidized to a brownish color, contains manganese pellets, and wherever found has a stratigraphic position between the yellow loess above and the till below. In some places this old loess-like clay contains dark organic matter as if it had formerly marked a soil horizon and supported vegetation. This was not found within the Belvidere lobe. One hundred and fifty borings in the extra-Belvidere drift showed an average of 3.9 feet of leached soil and loess and 4.2 feet of leached till over calcareous till with limestone pebbles, making a total of 8.1 feet of leached material as compared with 4 feet on the Belvidere lobe. (See Table I and also Fig. 3.) Since loess leaches more rapidly than till, it is also to be noted that the figures for the Illinoian area include a greater proportion of till than for the Belvidere lobe, and furthermore that 23 per cent of the borings failed to reach the calcareous zone in the Illinoian area, whereas only 6 per cent

failed to reach it in the Belvidere area. The average depth of leaching for the Illinoian given above is therefore something less than the actual.

Significance of these differences.—It is pertinent to inquire whether or not the differences between the Belvidere drift and the Illinoian drift can be explained on some other basis than on differences in age. That the drift is more weathered in one area than in another may be due to differences in the character of the material, or to differences in climate, or to differences in age. If the drift of the Belvidere area were composed of a tighter clay than that of the Illinoian area, such as might be derived from the belt of Maquoketa shale east of Belvidere, the leaching of the one would proceed at a less rapid rate than the leaching of the other; likewise the depth of oxidation, but less so the degree of oxidation at the surface. The geologic map of Illinois and the glacial map reveal that there is no correspondence between the belt of Maquoketa shale and the area of Belvidere drift. Besides, it is not possible on this basis to account for the difference in erosional expression of the moraines of the two areas, or the difference in degree of oxidation of the surficial portion, or the difference in concentration of the residual pebbles, or the difference in the stratigraphic relations of the buff loess, or the presence of the old loess-like silt and old soil and gumbotil in one area and not in the other. There are no differences in climate and no reasons for thinking that there have been between these two adjoining areas. A greater age for the Illinoian drift than for the Belvidere drift is the only explanation which satisfactorily explains all the facts.

The age of the drifts.—Table I summarizes the depth of leaching of various drifts, including the Belvidere drift, Bloomington drift, and Illinoian drift, based on the number of borings. Figure 3 shows graphically the differences in the depth of leaching of these drifts. All of the data indicate that the drift outside of the Belvidere Lobe is Illinoian in age. Comparing the Belvidere and Bloomington drifts, it will be seen that there is a slight difference in favor of the greater age of the Belvidere drift. But in the opinion of the writer, the major divisions of the Pleistocene cannot be made on such slight differences, and since there are Early Wisconsin moraines in

southern Illinois outside of the Bloomington, the writer prefers to correlate the Belvidere lobe with one of these, more plausibly the Champaign drift, inasmuch as the two are more nearly equivalent in the strength of their marginal expression and in the feebleness of their outwash deposits.

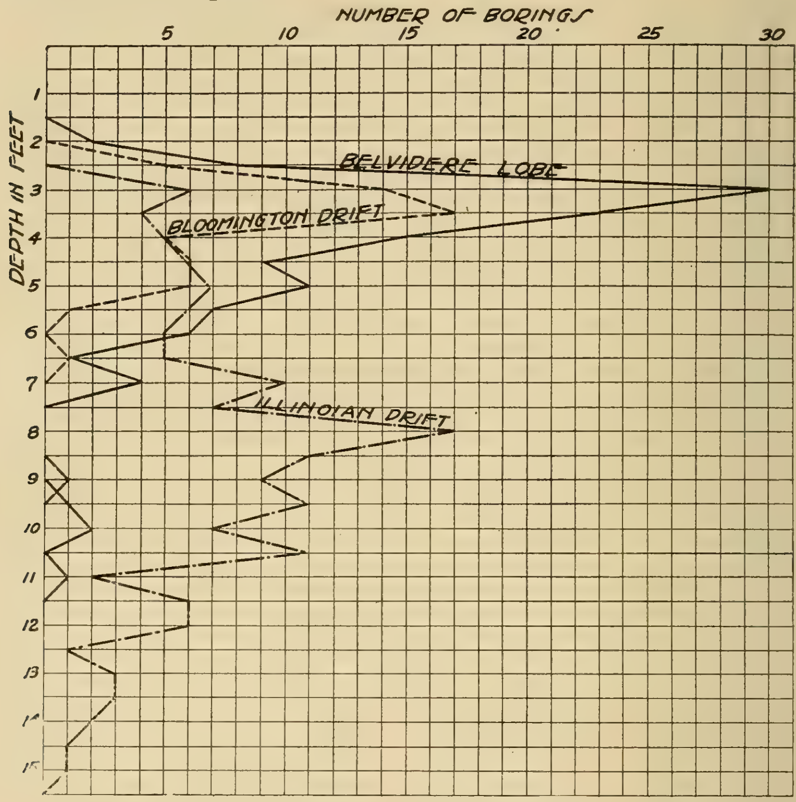

FIG. 3.—Graphs showing the number of borings recording a certain depth of leaching in the Belvidere, Bloomington, and Illinoian drift areas.

The source of the drift.—The question has been raised by Mr. Leverett, of the United States Geological Survey, as to whether or not the drift in the vicinity of Belvidere was deposited by a Green Bay lobe or by a protrusion of the Lake Michigan lobe. The presence of short morainic ridges south of the Kishwaukee River which trend northwest-southeast, offers some support to the former idea,

but there are serious objections to such an interpretation. If these ridges were the product of a southwestward-moving glacier, we should expect to find (1) the ridges represented north as well as south of the Kishwaukee River, (2) the drift of northern Boone County showing the same evidences of age as that to the south, (3) the eskers trending northeast-southwest, (4) the striae on the bedrock trending northeast-southwest, and (5) the axis of such a lobe situated to the east. Checking on these points, it should be stated that (1) there is no continuation of these ridges north of the river; (2) the drift of northern Boone County is more weathered than that south of the Kishwaukee River and in places in the northern part the drift is separated from the overlying loess by an old soil, whereas no such relationship was found in the southern part; (3) an esker-like ridge less than ½ mile long situated about 1 mile south of Cherry Valley parallels the Kishwaukee River in a northeast-southwest direction, but a much larger esker on the upland near Irene station trends at right angles to this in conformity to the supposed radial flow of the Belvidere lobe; (4) striae have been observed on the bedrock at the quarry 1 mile southwest of Belvidere trending a few degrees north of west;[1] and (5) a projection of the axis of the Green Bay lobe would place it west of this area rather than east. The axis could scarcely lie east of this area without encroaching upon the territory which would more likely be occupied by the master lobe, the Lake Michigan lobe. Unfortunately the lithology of the till lends no aid in the solution, because the formations which would be crossed by a Green Bay lobe would be the same for this locality as those crossed by the Lake Michigan lobe.

The best explanation which the writer has to offer for these ridges is that their materials were deposited in re-entrant angles and crevassed zones of a radial-spreading lobe, the crevasses on this side of the lobe trending in a northwest-southeast direction. Melting was more rapid along these crevassed zones than elsewhere and with the ice and glacial waters continually bringing material forward, greater accumulations took place here than elsewhere beneath the ice. The quantity of gravel in these ridges is in harmony with this

[1] Rollin D. Salisbury and Harlan H. Barrows, "The Environment of Camp Grant," *Illinois Geological Survey Bulletin 39* (1918), p. 44.

hypothesis. The northwestward movement of the ice on this side of the lobe is borne out by the striae at the quarry southwest of Belvidere and by the trend of the large esker. This explanation is further supported by the restriction of the morainic belts to the Belvidere lobe and their disappearance to the southeast toward the central axis of the lobe. The protrusion of the Belvidere ice lobe from the main Michigan lobe blocked the valley of Piscasaw Creek and diverted its waters temporarily westward across the divide into Beaver Creek, and later during its recession impounded the waters of Rush Creek Valley in western McHenry County until they poured across the divide into Piscasaw Creek Valley. An inspection of the Belvidere topographic map, which shows these old channels, will make it clear that their explanation would be difficult on the basis of a southwestward-moving ice.

THE GREEN RIVER LOBE

The drift of the Green River lobe is mostly buried by the outwash sand and gravel from the Bloomington moraine and the Late Wisconsin Valley train of Rock River, but strips of this drift are exposed on the north and west sides and patches in the western part (see Fig. 2). The boundary of this lobe on the north side is definite for some 3 miles west of Eldena and 10 miles to the east and north, but less so to the west. On the south side the boundary is fairly definite.[1] The western limits cannot be definitely mapped, due to the patchy character of the drift, the heavy deposits of loess and sand on the upland, and the sand and gravel outwash on the lowlands; but there is reason to think that the ice blocked the old course of the Mississippi River in northeastern Rock Island County and caused its diversion across the rock divide south of Cordova. The evidence for this will be considered later.

The strip along the north side.—From a point near the north line of Lee County and about 10 miles west of the east line, a strip of relatively fresh drift up to six miles wide extends across the upland to the southwest to a point south of Dixon, thence north of west into the area northeast and north of Sterling, and thence south of

[1] This portion of the boundary is much like that drawn by Leverett for the south side of the Iowan drift, on Plate XII *U.S. Geological Survey Monograph XXXVIII;* otherwise the present mapping is in contrast to that referred to.

west into the lowland area southeast of Morrison. The valleys of Rock River and Elkorn Creek are the chief interruptions in the continuity of the belt. A low but definite ridge of thick drift marks the margin for about 2 miles west and south of Eldena and some 8 miles to the east and north, as shown in Figure 1. To the west the boundary is much less definite than could be desired, but the weathering of the drift and the relations of the drift to the loess indicate that the line which has been drawn marks approximately the limit of a relatively young drift. Ninety-three widely distributed borings along this strip showed an average of 1.2 feet of soil, 3.1 feet of non-calcareous loess, and 1.3 feet of leached till, making a total of 5.6 feet of leached or non-calcareous material. In repeated cases where the loess was thick enough to be calcareous, the till below was found to be calcareous and to contain limestone pebbles to the top, showing that no interval of weathering intervened between the deposition of the loess and the till of this strip. North of the margin of this strip, thick loess lies unconformably on the till. That is to say, either an old soil or humus muck or old non-calcareous loess-like silt or gumbotil lies between the two, or the calcareous zone of the loess rests upon leached and oxidized till. No exposure of gumbotil is known in the belt of younger drift except at one place along the east line of the southeast quarter of Sec. 33, T. 21 N., R. 10 E., south of a low portion of the marginal moraine, where there appears to be an absence of the younger drift. In the territory immediately north of the line, the total average thickness of leached till and loess is nearly twice as great as south of the line. The writer knows of no other adequate explanation for these phenomena than difference in age. As in the case of the Belvidere lobe, there is a paucity of outwash related to the younger drift, and a corresponding lack of kames in the moraine. Southeast of Dixon the Rock River appears to have been blocked by this ice lobe, as indicated not only by relatively fresh drift northeast of Sterling but by an old channel scar skirting the margin and comparable in size to the Rock River.

The strip along the south side.—South of the Green River sand plain and extending west from the Bloomington moraine at Sheffield to Geneseo, there is another strip of drift with thin loess, which appears to be of the same age as the strip of drift along the north

side. To the south is undoubted Illinoian drift heavily overlain with loess (see Fig. 1). For 6 miles west of the Bloomington moraine, the drift laps upon the highland and is bounded on the south by a belt of kames. Farther west to beyond Geneseo the strip is mostly low-lying and the border is marked by a thick accumulation of sandy loess which is known to have a thickness in excess of 35 feet. Over the Illinoian area south from here the loess thins somewhat and becomes finer, but maintains a considerable thickness, while over the strip of drift of youthful aspect it is scanty. At one place along the border, at the edge of the thick loess,[1] a shallow road-cut exposure was found which showed fresh till with limestone pebbles overlying a loess-like deposit, which resembles the loess southward from here, and which at various places is known to rest on weathered Illinoian drift.

Twenty-six borings on the strip of relatively fresh drift revealed an average of 1.2 feet of soil, 3.5 feet of non-calcareous loess-like silt, and 1.6 feet of leached till overlying calcareous till, making a total of 6.3 feet of non-calcareous material. It will be noted that this is so nearly like that of the strip on the north side of the Green River basin that they may properly be considered to be of the same age. Reference to Figure 1 will reveal that the exposures and auger borings which show positive evidence of an unconformity between the loess and the underlying till are situated almost entirely outside of the boundary of the relatively fresh drift, on both the north and the south sides of the basin.

THE AGE OF THE GREEN RIVER LOBE

It is to be kept in mind that the evidence for the differentiation of the Green River lobe from the Illinoian drift is based not only upon differences in leaching but also upon the occurrence of gumbotil, old soils, old loess-like silts and weathered zones between the Illinoian drift and the overlying loess and the general absence of such evidences in the Green River lobe. But the depth of leaching, based upon numerous and well-distributed auger borings, affords some measure of the comparative ages of the two drifts. In Table I, it will be seen that the average depth of non-calcareous materials

[1] About the center of the south line of Sec. 30, T. 16 N., R. 6 E., Bureau County.

in 119 different borings in the Green River drift area was 5.7 feet as compared with an average of 8.1 feet in the Illinoian drift area, based on 150 borings. (See Fig. 4 for a graphical presentation of

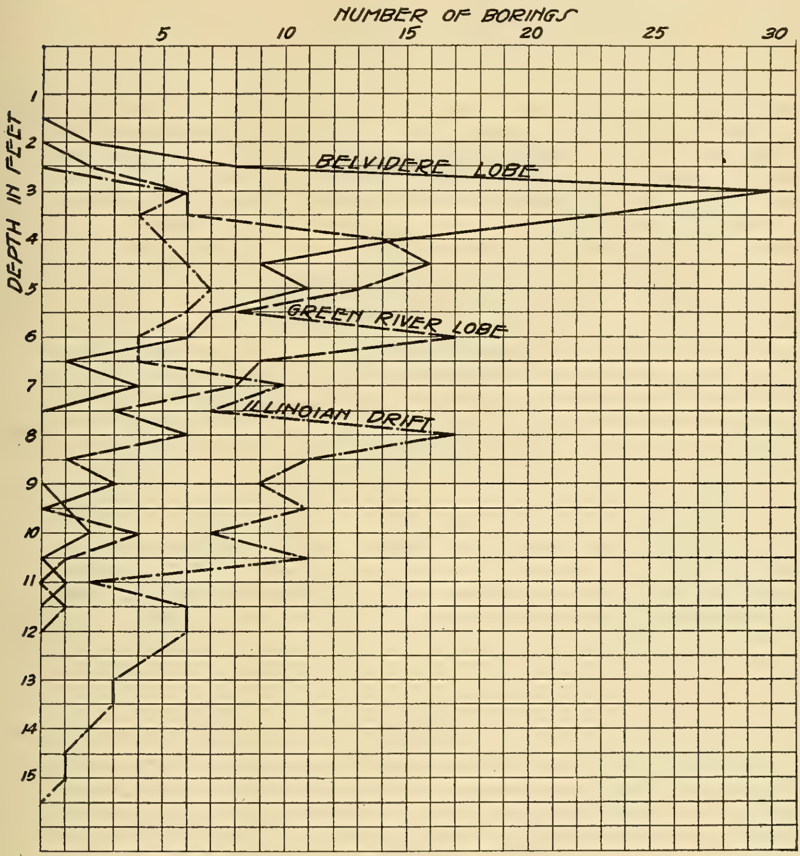

FIG. 4.—Graphs showing the number of borings recording a certain depth of leaching in the Belvidere, Green River, and Illinoian drift areas.

these data.) The average thickness of leached till is more than three times greater for the Illinoian drift than for the Green River drift, while the thickness of the overlying non-calcareous loess or loess-like silts is about the same.[1] It is also of interest to note that

[1] The thickness of the calcareous loess is not given, but it is much greater on the Illinoian than on the Green River drift; in many cases so thick that the auger failed to reach the till below, and hence such borings could not be used.

23 per cent of the 150 borings in the Illinoian area did not pass through the leached zone of the drift, while only 4 per cent failed to do so in the Green River area.

From this and the other data, there is no question in the mind of the writer but that the Illinoian drift is distinctly older than the Green River drift. The question now remains as to whether the Green River drift is Iowan or Early Wisconsin in age.

Table I gives comparative data for the leaching of the Green River drift and the Iowan drift in Iowa. The average thickness of non-calcareous materials resting upon calcareous till in the two areas is 5.7 feet for the Green River lobe and 5.2 feet for the Iowan drift. This would at first glance make it appear that the Green River drift is at least as old as the Iowan drift, but this non-calcareous zone includes thicker loess-like silt and thinner till in the former case than in the latter. Loess leaches much more rapidly than till because of its porosity and absence of pebbles, probably twice as fast according to the writer's data. If this ratio is used and the data evaluated correspondingly, the leaching of the Green River drift would compare with that of the Iowan drift in the ratio of 3.5 to 4.3, and with the Belvidere drift, 3.5 to 2.9. The data for the age of the Green River lobe are, therefore, not decisive. The Green River lobe is surrounded by thick loess, which, it is to be noted, is the same relationship as holds for the Iowan drift in Iowa.

THE TERMINUS OF THE GREEN RIVER ICE

Previous to the Green River ice invasion, the area involved was even more of a lowland than now, and invited the ice protrusion. The lowland became such in pre-Illinoian times by the erosion of the old Mississippi River and its tributaries when the master stream left its present valley near Cordova and flowed southeastward to the big bend of the Illinois River.[1] The Illinoian ice reversed the drainage to the west by way of a tributary valley, now the lower course of the Rock River, and thence over a divide to the west and south. That the Cordova gorge was not cut at this time is indicated by the

[1] Frank Leverett, "The Illinois Glacial Lobe," *U.S. Geological Survey Monograph XXXVIII* (1896), overprint of Plate VI; and "Outline of Pleistocene History of Mississippi Valley," *Journal of Geology*, Vol. XXIX (1921), pp. 615–26.

narrowness of the gorge, the rapids of the stream, and the occurrence of the Illinoian gumbotil horizon essentially to the valley wall on both sides (see Fig. 2) and high above the bottom of the gorge. If the gumbotil was developed on a plain under conditions of poor drainage, as set forth by Dr. G. F. Kay and J. N. Pearce,[1] the gorge could not have existed during Sangamon times. The diversion of the waters to this course seems to have taken place later and to be referable to the invasion of the Green River lobe. If so, the Green River ice must have reached the west side of the present Rock River Valley in northeastern Rock Island County. The loess is so thick here as to obscure all of the underlying deposits, so that there is no opportunity to trace the margin, but relatively fresh drift is exposed in patches on the east side of Rock River Valley. The cutting of the Cordova gorge must have been accomplished before the ice receded, which conclusion is consistent with the finding of small remnants of Late Wisconsin Valley train in the gorge.

[1] "The Origin of Gumbotil," *Journal of Geology*, XXVIII (1920), 89–125.

THE MINERALOGRAPHY OF THE FELDSPARS

PART II[1]

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INTRODUCTION

Part I of this study of the feldspars[2] is an attempt to summarize our knowledge of the physical-chemistry of this group of minerals. The method of attack is that of the phase rule.

[1] Contribution from the Department of Geology, University of Rochester, Rochester, New York.

[2] H. L. Alling, *Jour. Geol.*, XXIX (No. 3, 1921), 193–294.

It is sincerely hoped that the writer has already made clear that the feldspars are solid solutions and mixtures of solid solutions of three or more end members or "minals" as it was suggested that they be called.[1] It follows that the physical properties of the feldspars are continuously varying in proportion to the change in chemical composition. To make use of these properties for identification, since they are multiple component systems, they should be plotted as surfaces and not as curves.

Here, in Part II, the subject is carried further and additional aspects which were omitted before, because of the lack of space, are presented and discussed.

As our knowledge of the feldspar group, outside of crystallography, is to a very large degree confined to the plagioclase series, about one-half of the present paper is devoted to the potash-soda series. This system includes orthoclase, microcline, albite, "barbierite," anorthoclase, perthite, etc. It is not a little surprising to find that there is much uncertainty regarding the relationships between the different members of the system, as well as the correspondence between chemical composition and physical properties. Because the physical properties, including optical behavior, are a means of determining by the microscope the actual composition, this matter is presented in detail, chiefly by the aid of diagrams. But before the relation of physical properties to the composition can be thoroughly appreciated, it is necessary to understand the thermal-diagrams of the potash-soda series. There are a number of divergent opinions regarding the thermal-diagram, hence these ideas will first receive attention.

The potash-lime, barium, and strontium-bearing feldspars are treated next. Other topics are twinning, and aventurine feldspars.

THE POTASH SODA SERIES

THE DIAGRAM OF VOGT AND WARREN

The thermal diagram of the perthite feldspars in Part I (Fig. 4, p. 221) is only an approximation at the best. It is Warren's[2]

[1] *Ibid.*, p. 218.

[2] C. H. Warren, "A Quantitative Study of Certain Perthitic Feldspars," *Proc. Amer. Acad. Arts and Sci.*, LI (No. 3, 1915), 148.

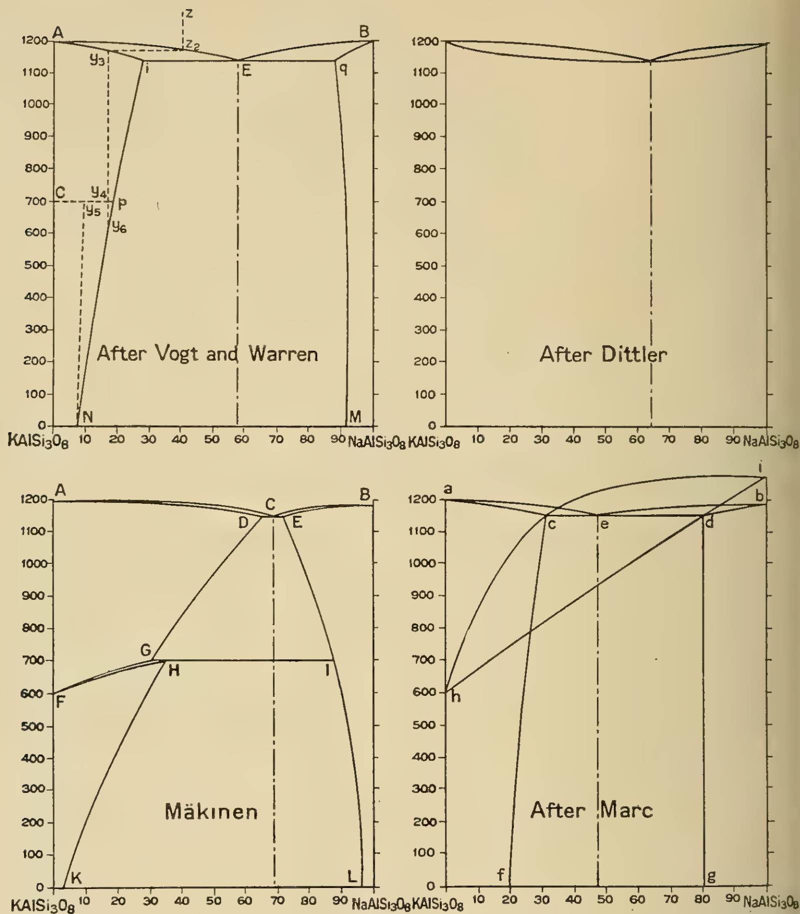


FIG. 1.—Thermal diagrams of the potash-soda feldspars after Vogt,* Warren,† Dittler,‡ Mäkinen,§ and Marc.|| These diagrams have been modified by the writer to bring them up to date, otherwise they represent the originals.

Legend for the diagram after Vogt and Warren:

A. "Melting point" of orthoclase (incongruent melting point).
B. Melting point of albite.
E. Eutectic point, 42 per cent of Or.
iN and *qM*. Boundaries of miscibilites. Solubility lines, Or and Ab.

* J. H. L. Vogt, *Tsch. Min. Petro. Mitt.*, XXIV (1905); XXV (1906); XXVII (1908).
† C. H. Warren, *Proc. Am. Acad. Arts and Sci.*, LI (No. 3, 1915), 148.
‡ E. Dittler, *Tsch. Min. Petro. Mitt.*, XXI (1912), 513.
§ E. Mäkinen, *Sonderadb. aus. Geol. Foren. Foerhandl.* XXXIX (No. 2, 1917), 121–84.
|| Robert Marc, *Chemische Gleichgewischtslehre*, p. 102.

C. Temperature horizontal, inversion of orthoclase to microcline ipy_2N. Solubility line when orthoclase inverts to microcline.
N. Or 92 Ab 8, approximate.
M. Or 6 Ab 94, approximate.
i. Or 72 Ab 28.
q. Or 12 Ab 88.

Legend for the diagram after Dittler:
Minimum point. Or 36 Ab 64.

Mäkinen's legend:
A. "Melting point" of orthoclase, 1190° C.
B. Melting point of albite, 1180°.
C. Eutectic point 30 per cent of Or.
DE. Miscibility gap. Solidification of the melt. Greatly exaggerated.
ADGF. Stable field of homogeneous monoclinic solid solutions (orthoclase, sanidine, and soda-orthoclase).
BEIL. Stable field of homogeneous triclinic solid solutions (albite, anorthoclase).
DEIGH. Complex, two-phase field, of monoclinic potash feldspar and triclinic soda feldspar solid solutions (orthoclase-perthite, crypto- and microperthite).
GHF. Complex, two-phase field, of monoclinic and triclinic potash feldspar solid solutions (no examples found in natural feldspars). (?)
FHK. Stable field of homogeneous triclinic potash feldspar solid solutions (homogeneous microcline).
HILK. Complex, two-phase field, of triclinic potash feldspar and triclinic soda feldspar solid solutions (microcline-perthite and antiperthite).
See text for criticism of Mäkinen's diagram.

Marc's legend:
a. Melting point of orthoclase.
b. Melting point of albite.
c. Eutectic point of monoclinic orthoclase-rich solid solution and triclinic albite-rich solid solution.
cf and *dg*. Boundaries of miscibilites. Solubility lines.
h. Transition point monoclinic $\rightleftarrows$ triclinic potash feldspars.
i. Transition point monoclinictr $\rightleftarrows$ icilinic soda feldspars.
hdi. Boundaries of triclinic condition.
hci. Boundaries of monoclinic condition.
Interval *hcidh*. Transition interval.
Whether the transition point *i* is situated above the melting point *b* has not been determined.

modification of Vogt's[1] original (Fig. 1, Part II). It shows a eutectiferous system with the eutectic point at 42 per cent orthoclase, 58 per cent albite (plus anorthite), with inclined solubility curves.

[1] J. H. L. Vogt, "Physikalisch-chemische Gesetze der Krystallisationsfolge in Eruptivgesteinen," *Tsch. Min. Petro. Mitt.*, XXIV (1905), XXV (1906), and XXVII (1908).

The possibility of inversion[1] of orthoclase to microcline is not provided for in Part I, although Warren's figure introduced it. This change in modification he emphasized as a partial explanation of the formation of perthitic intergrowths.[2] The other suggested modes of origin are the "unmixing"[3] or "ex-solution"[4] of the two phases upon falling temperature and the crystallization of the eutectic. It is well to note that the diagram relates to pegmatitic feldspars only and does not apply to feldspars of other origins.

One of the difficulties with the Vogt-Warren diagram is that it was based upon chemical and quantitative microscopic studies[5] of pegmatitic feldspars at normal pressures and temperatures, and was not checked by thermal analysis. Had these data been available, it is believed that a different position of the eutectic point would have been proposed, as well as certain other conclusions drawn. The reason for this is that the proportion of the two feldspar phases in a given intergrowth depends upon the amount of exsolution that has taken place. Rapid cooling and the absence of mineralizers promote excessive undercooling and thereby retard exsolution. This condition prevails in many surface and porphyritic rocks, and hence we should not draw too general conclusions from special or local phenomena.

THE DIAGRAM OF DITTLER

Dittler[6] investigated the potash-soda series, and found that natural specimens of various composition melt between 1125° and 1200° C. either incongruently[7] or congruently, and came to the conclusion that the form of the diagram should be a series of solid solutions with a minimum.[8] (Fig. 1, Part II.)

[1] See J. B. Ferguson, *Science*, N.S., L (1919), 544–46.

[2] J. H. L. Vogt, *Tsch. Min. Petro. Mitt.* (2), XXIV, 537–41; Alfred Harker, *Natural History of Igneous Rocks*, 1909, pp.259–260.

[3] C. H. Warren, *Proc. Amer. Acad. Arts and Sci.*, LI (1915), No. 3.

[4] The writer. See Part I, p. 222, footnote.

[5] The Delesse-Rosiwal method. See Arthur Holmes, *Petrographic Methods*, p. 313.

[6] E. Dittler, "Die Schmelzpunktskurve von Kalinatronfeldspäten," *Tsch. Min. Petro. Mitt.*, XXXI (1912), 513.

[7] See Morey and Bowen, *Amer. Jour. Sci.* (5), IV (1922), 1–22.

[8] Type III of Bachius Roozeboom.

The same conclusion was reached by Johansson[1] and Vegard.[2]

The suggestion that the diagram of the potash-soda series is a series of solid solutions with a minimum melting point, is one that Warren formerly held[3] in explanation of the homogeneity of the soda-rich phenocrysts of the porphyries in the region of the Blue Hills and Quincy, Massachusetts. Warren regarded this form of diagram as portraying the conditions prevailing at high temperatures, but with falling temperature exsolution took place. He later abandoned this view because it is not applicable to the crystallization of granites, and considered the homogeneous alkalic feldspars, such as anorthoclase, to be metastable crystallizations. It seems to the present writer that Warren in seeking a *single* diagram for the potash-soda series abandoned an idea well worth considering. If a *series* of diagrams, as later proposed, is correct, then we can retain Warren's idea as applicable to such metastable solid solutions, but not to feldspars crystallizing under plutonic conditions.

Dittler's diagram is open to the criticism that he determined the melting point interval, the area between the solidus and liquidus, by Doetler's microscopic method. Serious errors are known to be associated with this method, as pointed out by Day.[4]

The difficulty with the Dittler diagram is that it applies to rapidly cooled metastable feldspars and not to others. The suggestion is therefore offered that a diagram which combines the diagrams of Vogt and Dittler is more likely to approach the truth than either one alone.

COMBINATION OF THE TWO EXTREMES

In Part I the combination of these extremes was attempted in Figure 5 (p. 225). The two binary diagrams are shown related to each other through the degree of equilibrium, the solid solution diagram with a minimum being the unstable one, while the eutectiferous diagram represents the system when perfect equilibrium obtains.

[1] H. E. Johansson, "Om fäldspaternas sammansättning och bildnings förhållanden," *Diese Zeitschr.*, XXVII (1905), 338. This paper the writer has not seen, as it is reported by Mäkinen ("Über die Alkalifeldspäte," *Sonderabd. aus. Geol. Föreningens.*, I (1917), to occur only as a "separate" or abstract. It is not generally known.

[2] Vegard, "Die Konstitution der Mischkrystalle," *Phys. Zeitschr.*, XVIII (No. 15, 1917), 33, 93–96.

[3] C. H. Warren, *Proc. Amer. Acad. Arts and Sci.*, XL (No. 5, 1913), 317–23.

[4] A. L. Day, *Fortschr. der Min. Kryst. u. Pet.*, IV (1914), 134–37.

THE DIAGRAM OF MÄKINEN

Mäkinen, in his recent and valuable paper,[1] offers a thermal diagram that may well be considered as an intermediate diagram (such as the writer suggested in Part I, p. 225). It is perhaps to be inserted close to the front plane in the figure. Mäkinen makes the miscibility gap (Mischungslücke) line *DE* in Figure 1, Part II, very short, covering only 10 per cent composition from about 66 per cent Ab to 74 per cent Ab, which he says is greatly exaggerated. He places the eutectic point at 70 per cent albite while Vogt placed it at 58 albite.[2]

Watts[3] has made a similar suggestion that the eutectic point should be nearer to albite than Vogt placed it. Here again we must remember that artificial mixtures of natural feldspars were melted and from such thermal data the conclusions were drawn. It seems that these apparently conflicting ideas can be reconciled by stating that a *single* binary diagram is not sufficient to express the crystallization of *all* potash-soda feldspars, but that a series of diagrams is necessary, grading from a simple eutectiferous system to a system of solid solutions with a minimum. Mäkinen points out[4] that pegmatitic feldspars have a *restricted* range in composition compared with porphyritic or plutonic feldspars on the one hand, and *greater* compositional freedom than drusy and adularious[5] feldspars on the other. This can be interpreted to mean that the diagram for adularious feldspars should show a eutectiferous system with the solubility lines close to the sides, indicating very limited solubility and consequently very restricted compositional freedom. The eutectic point for adularious feldspars is not known, but a reasonable position, it seems to the writer, would be about 50 per cent albite. Thus in a three-dimensional model (Fig. 2, Part II) this eutectic at 50 per cent Ab could be connected with the minimum point of the solid

[1] Eero Mäkinen, "Über die Alkalifeldspäte," *Sonderabd. aus. Geol. Föreningens. Förhandl.*, XXXIX, H. 2 (February, 1917), 149.

[2] The variation in the position of the eutectic point may well be due to the shift brought about by metastable and labile conditions. See C. H. Gulliver, *Metallic Alloys*, 1913, pp. 165–67, and J. V. Elsden, *Principles of Chemical Geology*, 1910, pp. 114–16, 153.

[3] A. S. Watts, "The Feldspars of the New England and North Appalachian States," *U.S. Bur. Mines Bull. 92*, 1916.

[4] *Op. cit.*, pp. 132–33, fig. *A–E*, Fig. 1-3, Fig. 2, Part II.

[5] *Die Feldspäte der Adulardrusen.*

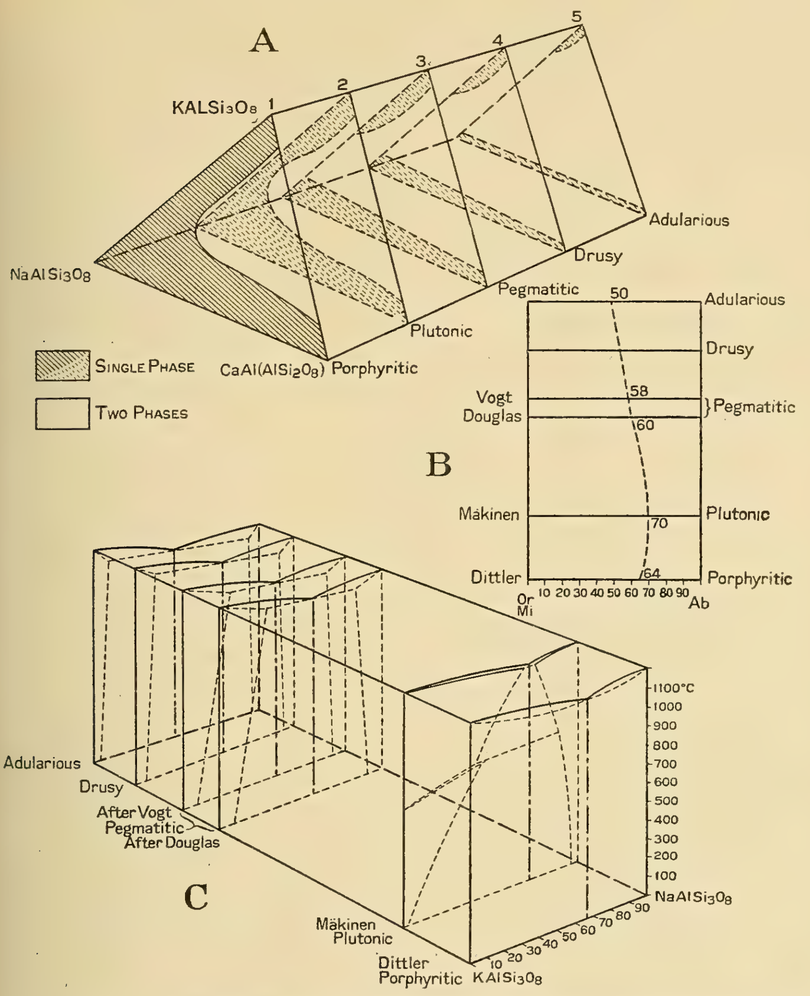


FIG. 2.—*A*. Three-dimensional compositional diagram showing fields occupied by natural feldspars of different origins. It indicates that porphyritic feldspars have a greater range in composition than those of any other origin and may even bridge the eutectic gap as sanidine and anorthoclase. It shows why sanidines may be rich in soda while adularias more closely approach the theoretical composition, $KAlSi_3O_8$. Arranged from Mäkinen's diagrams.

B. Projection of an arranged series of thermal diagrams of the potash-soda feldspars, showing possible variation in the position of the eutectic point for feldspars of different origins. This diagram is offered with full appreciation that it is based upon uncertain data.

C. Stereogram of arranged thermal diagrams of the potash-soda series showing that no *one* diagram can express the crystallization of *all* feldspars. From these diagrams the reader is to see a solid model; any transverse cross section of which is a diagram of feldspars of a particular origin.

solution diagram, having the minimum at a point about 64 per cent albite. The writer believes that Mäkinen's diagram roughly represents the conditions prevailing during the crystallization of plutonic feldspars. Douglas[1] has suggested that the eutectic point should be placed at 40 per cent orthoclase, 60 per cent albite. Such a diagram, all other matters being the same, may be, therefore, inserted in the three-dimensional model between that of Vogt and of Mäkinen. It is hoped that in spite of the many uncertainties concerning the thermal diagram of the potash-soda series, the suggestions offered in Figure 2 will be helpful in securing a proper conception of the mode of crystallization of all feldspars of this range of composition.

THERMAL STUDIES

Audley,[2] from commercial experience, says:

> The destruction by heat of the crystalline condition of a silicate does not always result in the immediate production of a homogeneous and transparent substance—that is a glass. (Potash) feldspar, for example, between 1100° and 1200° C. gives a white material resembling porcelain or devitrified glass in appearance. The feldspar has really become decomposed.

Morey and Bowen[3] have investigated this phenomenon in the Geophysical Laboratory and have shown that potash feldspar, either orthoclase or microcline, has no true melting point, that is, it melts incongruently at about 1170° C., for pure (artificial) potash feldspar, breaking up into liquid and leucite. This temperature is lowered a little with increasing amounts of other feldspar components. This necessitates the use of a binary diagram to show the thermal properties of orthoclase (or microcline) which is a binary compound of leucite and silica (Fig. 3, Part II).

$$KAlSi_2O_6 + SiO_2 \leftrightarrows KAlSi_3O_8$$
$$\text{Leucite} + \text{Silica} \leftrightarrows \text{K-feldspar}$$

[1] J. A. Douglas, "On Changes of Physical Constants in Minerals [by heating]," *Quar. Jour. Geol. Soc.*, LXIII (1907), 159.

[2] J. A. Audley, "Silica and the Silicates," *Van Nostrand*, 1921, p. 46.

[3] G. W. Morey and N. L. Bowen, "The Melting of Potash Feldspar," *Amer. Jour. Sci.* (5), IV (1922), 1–22.

With the above modification as to the nature of the melting of potash feldspar, the diagrams so far offered represent the present status of our knowledge.

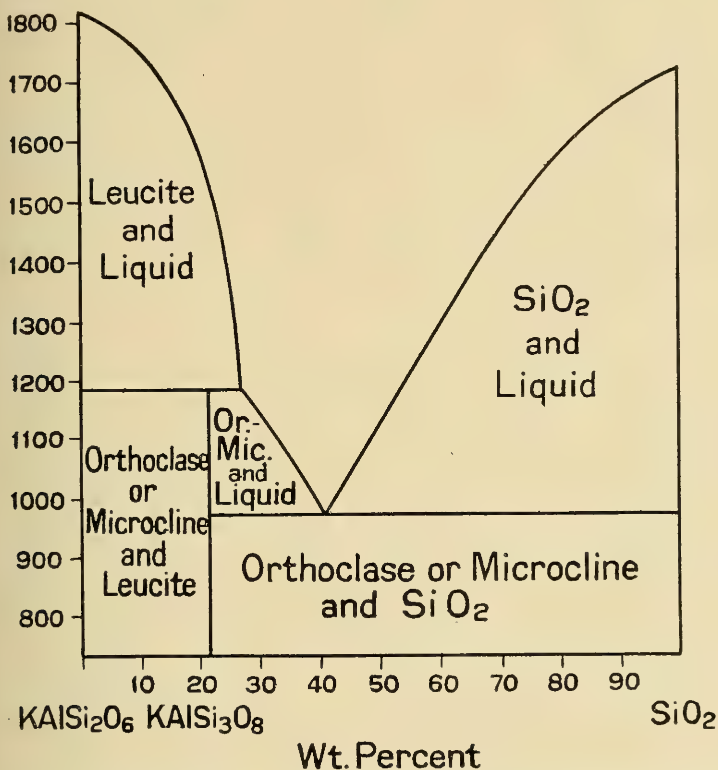


FIG. 3.—Thermal diagram of the system leucite-silica, showing incongruent melting of the intercomponent compound $KAlSi_3O_8$ (orthoclase-microcline), after Morey and Bowen. *Amer. Jour. Sci.* (5), IV (1922), 1–22.

DIMORPHISM

Orthoclase vs. microcline.—The writer, in Part I, agreed with Vogt,[1] Barbier,[2] Clarke,[3] and Harker[4] that orthoclase and microcline are dimorphous forms of the same substance. To secure evidence

[1] J. H. L. Vogt, as cited by C. H. Warren, *Proc. Amer. Acad. Arts and Sci.*, LI (No. 3, 1915), 144.

[2] Ph. Barbier, "Researches sur la composition chimique de feldspaths potassique," *Bull. Soc. Franç. minéral.*, XXXI (1908), 152–67.

[3] F. W. Clarke, *U.S. Geol. Surv. Bull. 588*, 12.

[4] *Op. cit.*, p. 258.

PLATE I

All photomicrographs taken with cross nicols, ocular $\times 7.5$, and objective, 16 mm.

A. Zonal plagioclase liparite-perlite, Pushi Hrad, Hungary. (L-91)

B. Zonal anorthoclase-crypto-microperthite in Kekequabec soda granite, Minnesota. See Grant, *Amer. Geol.*, XI (1893), 383–89, and (at present unpublished) Ph.D. thesis of Kennedy, University of Illinois (kindness of William S. Bayley). Described as an "intergrowth of albite with either soda orthoclase or soda microcline." (1150)

C 1. Adularia, St. Gottard Region, Eggerhorn, Switzerland. ($Or_{83.5}Ab_{9.5}An_{7.0}$.) Slide prepared with great care by the writer, showing phantom, incipient microcline twinning. Considered as representing inversion of orthoclase (adularia) to microcline brought about by the grinding incident to preparation of the slide. (989)

C 2. Same as *C* 1. Slide prepared by W. H. Tomlinson, probably with less care, showing greater development of phantom microcline twinning. (989 *A*)

D 1. Adularia, St. Gottard Region, Scopi, Switzerland. (Or 88 Ab 9 An 3.) Slide prepared by Tomlinson showing incipient twinning. (988)

D 2. Same as *D* 1, prepared with extreme care by the writer, showing not a trace of phantom twinning. The parallel lines are cleavage cracks. (998 *A*)

E. Crypto-microcline, pebble, Pacific Coast, phenocryst of a porphyry. (A. F. Rogers.) (Approx. $Or_{80}Ab_{18}An_{2}$.) The light area in the center is quartz. (1438)

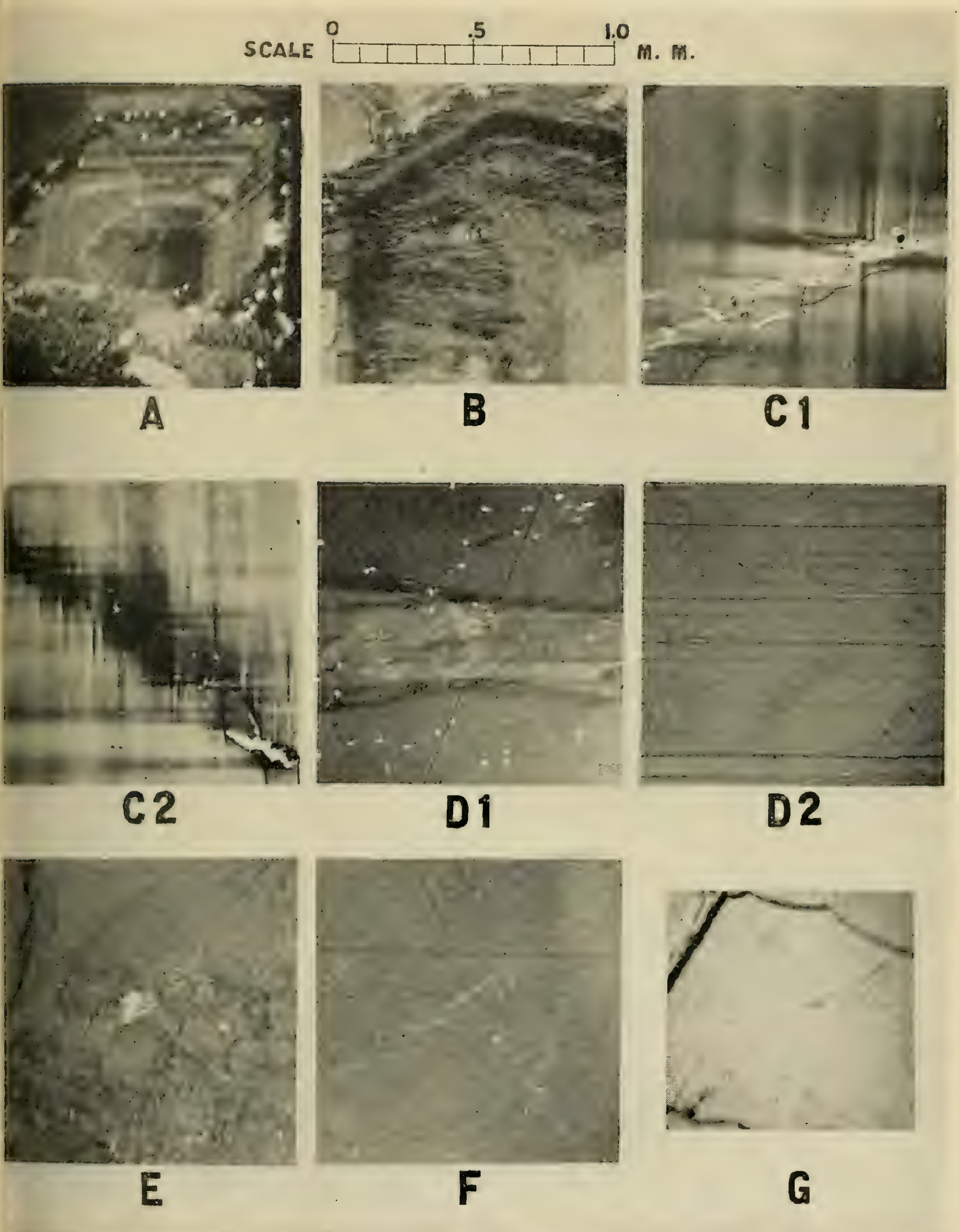
F. Moonstone ($Or_{75}Ab_{23}An_{2}$). Anorthoclase-cryptoperthite, from Ceylon. See Kozu, *Sci. Rept. Topoku Univ.*, Series III, Vol. I, No. 1, showing incipient development of perthite. (1394)

G. Crypto-soda microcline, sanidine, Viterbo, Italy, showing development of crypto-microcline twinning.

[1] O. Maschke, *Pogg. Ann.*, CXLV (1872), 565–68; *Weidemann's Ann.*, XI (1880), 722–34; J. L. C. Schroeder van der Kolk, *Zeitschr. f. wiss. Mikroskopie*, VIII (1892), 456–58.

[2] Pyrometric (Seger) cone determination. Hence, as Mäkinen says, only approximate.

[3] Specimen 959.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of the true relationship between the two minerals is a very difficult matter. Since dimorphism (isomerism) is a thermal property of matter, it is reasonable to expect that the effect of "heat treatment" on natural feldspars might throw light upon this problem.

Merian and Wahl[1] through heating of fragments and thin pieces endeavored to convert microcline into orthoclase. In spite of heating to the melting point, they observed no change in the optical orientation of the specimens. Mäkinen made similar experiments which, while they throw considerable light upon the nature of anorthoclase, leave some doubt regarding the relation between microcline and orthoclase. He says[2] (in translation): "Although the expected transition (inversion) of microcline into orthoclase is indicated by these researches, still one does not dare to use this in support of the polysymmetry theory [of Groth].[3] Apparently the rate of transition is so slow and requires so long a time that it (inversion) cannot be demonstrated in the laboratory." He says that the transition from orthoclase to microcline is a "secondary"[4] process. "However, it gives no reason to assume that the final modification should be enantiotropic, i.e., that orthoclase can be transformed into microcline but not microcline into orthoclase." Morey and Bowen[5] found that there is "no appreciable difference of behavior connected with the difference in form of orthoclase and microcline," in breaking up into leucite and liquid at about 1170° C.

In Part I the results of heating the microcline-microperthite (hypoperthite) from San Diego County, California,[6] were offered on page 267, in support of inversion of orthoclase into microcline by "annealing" at about 900° C. The writer found that microclinic twinning was produced by such treatment; the amount of twinning formed being in proportion to the time the material was subjected to heat. Further study of the material has caused the writer to question the evidence. An examination of the optical

[1] A. Merian and Wahl, *Neues Jahrb. f. Min.*, I (1884), 195.

[2] Eero Mäkinen, "Über die Alkalifeldspäte," *Geol. Fören. Förhandl.*, XXXIX, H. 2 (February, 1917), 127.

[3] Paul Groth, "Chemical Crystallography" (Marshall) Wiley, 1906, 7. See Harker, *op. cit.*, p. 258; also Wahl, *Ofversikt af Finska Vet. Soc. Förh.*, L (1906–7), No. 2.

[4] In the original the word is "sekulärer," which the writer suspects is a typographical error for "sekundärer."

[5] Morey and Bowen, *Amer. Jour. Sci.* (5), IV (1922), 1–21. [6] Specimen 958.

constants leads to the conclusion that the composition was about: $Mi_{64.3}\ Ab_{28.9}\ An_{3.8}\ Qz_{3.0}$. A chemical analysis of the same material was made for the writer by H. B. Croasdale[1] with the following results:

TABLE I

HYPOPERTHITE, SAN DIEGO COUNTY, CALIFORNIA

SiO_2	....	64.40	....	....	63.61	....
Al_2O_3	....	19.46	....	....	19.48	....
Fe_2O_3	....	0.12	....	....	0.08	....
FeO	....	0.22	....	....	0.22	....
MgO	....	0.13	....	....	0.11	....
CaO	....	0.42	....	....	0.51	....
Na_2O	2.35*	2.40	2.46†	2.00*	1.96	1.92†
K_2O	14.38*	14.46	14.55†	14.70*	14.77	14.83†
H_2O	....	0.12	....	....	0.15	....
Total	....	101.73	....	....	100.89	....

* By the J. Lawrence Smith Method—H_2PtCl_6.
† By the use of $HClO_4$.

It was found when the material was recast that it was necessary to calculate an appreciable amount of "nephelite" or "carnegieite,"[2] as can be observed from Table II.

Thus it has turned out to be a very different feldspar than was formerly supposed. The presence of this component may well account for the development of twinning and for the failure to determine by *optical means* the actual composition. Carnegieite is reported to twin according to the albite and pericline laws, often simultaneously.

The heating of normal feldspars, lacking the nephelite-carnegieite component, leaves the matter of the isomerism of orthoclase-microcline in doubt, although long heating at 900° C. in some instances seemed to indicate a possible inversion of microcline into orthoclase, and long heating of orthoclase at 700° C. did produce a slight increase in the amount of twinning.

The lack of success of these thermal studies is offset by the results of plotting the values of the specific gravities of the potash-soda-lime feldspars. The data employed consist of about 80 feldspars, most of them natural, a few artificial. It is a regrettable fact that

[1] Of the Fraser Laboratories, New York City.

[2] $Na_2Al_2Si_2O_8$. H. S. Washington, *Jour. Geol.*, XVI (1908), 10; H. S. Washington and F. E. Wright, *Amer. Jour. Sci.* (4), XXVI (1908), 187, XXIX (1910), 52–70, and XXXIV (1912), 555.

more data are not forthcoming; for it is truly surprising to find that while many analyses are available, the values of the specific gravity are only occasionally given. In drawing conclusions from

TABLE II

RECAST OF HYPOPERTHITE, SAN DIEGO COUNTY, CALIFORNIA

	No. 958-1						
	SiO_2	Al_2O_3	CaO	Na_2O	K_2O	Total	Total/100
Percentage	63.70	19.24	0.41	2.35	14.30	....	....
Mol. ratio	1.0560	.1884	.0073	.0379	.1518	....	....
Or	.9108	.1518	....	....	.1518	84.63	84.2
Ab	.0822	.0137	....	.0137	....	7.20	7.1
An	.0146	.0073	.0073	....	....	2.04	2.0
Ne	.0484	.0242	....	.0242	....	6.89	6.7
Total	....	....	....	....	....	100.76	100.0
	No. 958-2						
Percentage	63.61	19.48	0.51	1.96	14.77	....	....
Mol. ratio	1.056	.1905	.0091	.0316	.1568	....	....
Or	.940	.1568	....	....	.1568	87.47	86.5
Ab	.0519	.0086	....	.0086	....	4.55	4.5
An	.0182	.0091	.0091	....	....	2.53	2.5
Ne	.0459	.0229	....	.0229	....	6.53	6.5
Total	....	....	....	....	....	101.08	100.0

AVERAGE

	Per Cent
Orthoclase or Microcline	85.35
Albite	5.80
Anorthite	2.25
Nephelite	6.60
	100.00

such miscellaneous data we must remember that the chemical analyses of today are vastly superior to those collected and published by Dana, Hintze, Doelter, Herzenberg and others.[1] The chemical analyses were recast into terms of three components,

[1] See H. S. Washington and H. E. Merwin, *Amer. Jour. Sci.* (5), I (1921), 20. Larsen says (*U.S. Geol. Surv. Bull. 679* [1921], p. 6): "Much further work on the optical constants and more complete and accurate data on nearly all the minerals are needed . . . . a highly accurate determination of physical properties [etc.] of a mineral is of comparatively little value unless the data obtained are definitely tied to a chemical analysis." See Arthur Holmes, *Petrographic Methods and Calculations.*

K-, Na-, and Ca- feldspars. If the sum of the three feldspars was appreciably below or above one hundred, the analysis was considered inferior, or the specimen abnormal, and it was consequently omitted. Thus there has been some selection of the available data by elimination. Upon a triangular base each recast analysis was located according to the composition and indicated by a point. On each point a pin, whose length (height) represented the value of the specific gravity, was erected. In this manner a "peg model" was constructed. It is very evident from the model, or three-dimensional graph, that there are two groups, one set of pins being longer, standing higher, than the other group. As the majority of the pins giving the values of specific gravities of feldspars called in the literature "orthoclase" are longer than those called "microcline," the obvious interpretation is that orthoclase, soda orthoclase, "monoclinic" anorthoclase, as well as orthoclasic phases in perthitic feldspars, are heavier than the microclinic equivalents of these. This idea was suggested in Part I (Fig. 6, p. 228) but the writer, through the construction of the peg model, feels that such an interpretation can now be entertained with more confidence.

A single and constant physical or chemical difference between orthoclase and microcline is sufficient to establish a case of dimorphism. Apparently here the specific gravities furnish the desired evidence.

The relation of specific gravity to composition is taken up in detail later.

Albite and "barbierite."—Barbier,[1] Prost,[1] Clarke,[2] Shaller,[3] and others have reached the conclusion that there is a monoclinic modification of the soda component which the latter named barbierite. A chemical analysis of the "barbierite" from Kragerö, Norway, is as follows:

SiO_2	67.00
Al_2O_3	19.12
CaO	0.78
K_2O	1.15
Na_2O	11.74
	99.79

[1] Barbier and Prost, "Sur l'existence d'un feldspath sodique monoclinic isomorphe de l'orthoclase," *Bull. Soc. Chem.*, III (1908), 894.

[2] F. W. Clarke, *U.S. Geol. Surv. Bull. 588*, 35.

[3] W. T. Shaller, *Bull. Soc. Min.*, XXXIII (1910), 320; *Zeitschr. f. Kryst.*, L (1911), 347; *Jour. Wash. Acad. Sci.*, I (1911), 177; *U.S. Geol. Surv. Bull. 509* (1912), p. 40; Barbier and Gonnard, *Bull. Soc. Min.*, XXXIII (1910), 81.

An attempted recast results in the absurd sum of 109.69 per cent for the total feldspar and a deficiency of 7.49 per cent SiO_2 and 1.21 per cent Al_2O_3, as is shown in Table III:

TABLE III

	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	Total
Percentage.........	67.00	19.12	0.78	1.15	11.74	99.79
Mol Wt...........	60.3	102.2	56.07	94.2	62.0	....
Mol ratio..........	1.112	.1870	.0139	.0122	.1894	....
K-feldspar.........	.0732	.0122	....	.0122	....	6.82
Na-feldspar........	1.1364	.1894	....	....	.1894	99.56
Ca-feldspar........	.0278	.0139	.0139	....	....	3.31
Total.........	1.2374	.2155	.0139	.0122	.1894	109.69
Deficiency.....	.1254	.0185	....	....	....	....
Percentage.....	7.49	1.21	....	....	....	....

Mäkinen[1] has already questioned the value of this analysis when he says (in translation): "The occurrence of a monoclinic sodium feldspar was recently regarded by Barbier and Prost as proved because they found a so-called monoclinic feldspar from Kragerö which contains 11.74 per cent Na_2O, 0.78 per cent CaO, and only 1.15 per cent K_2O. The sum of K_2O+Na_2O+CaO, over against SiO_2 and Al_2O_3 is still altogether too low and their analysis is to such a degree defective that they themselves can scarcely regard it as satisfactory." It is of course quite possible that their analysis is indeed defective, but when the possibility is considered of nephelite-carnegieite being present, then the results of recasting are understandable as in Table IV:

Still there is room for improvement. Can it be that the presence of hexagonal nephelite in a soda-rich feldspar to the extent of nearly 9 per cent renders the whole monoclinic, *without the possibility of any dimorphism of* $NaAlSi_3O_8$? Possibly. The writer is unable to offer any suggestion that bears on this question.

The writer endeavored to secure from Dr. Schaller[2] definite information regarding barbierite. Dr. Schaller reported[3] that the

[1] Eero Mäkinen, "Über die Alkalifeldspäte," *Geol. Fören. Förhandl.*, XXXIX, H. 2 (February, 1917), 122.

[2] Through Mr. English of Ward's Natural Science Establishment.

[3] August 8, 1918.

Photomicrographs of Unusual and Common Feldspars

PLATE II

A. Microcline-microperthite (hypoperthite), (approx. $Mi_{60}\,Ab_{37}\,An_2\,Hem_1$). Sunstone, Delaware County, Pennsylvania. White areas, albite ($Mi_2Ab_{97}An_1$). Dark areas, soda microcline ($Mi_{80}Ab_{17}An_3$), showing a coarse type of intergrowth. (974)

B. Nephelite bearing anorthoclase, chesterlite ($Or_{42}Ab_{45}An_3Ne_{10}$). Poor House Quarry, Chester County, Pennsylvania, showing queer type of wavy extinction.

C. Microcline-microperthite near Unionville, Chester County, Pennsylvania (approx. $Mi_{57}Ab_{34}An_5Qz_4$), showing irregularly bordered albite spindle (bleb) in microcline. (996)

D. Microcline-microperthite (hypoperthite) from pegmatite of Yonkers gneissoid granite, Valhalla, New York, a typical pegmatitic feldspar.

E. Cassinite, Blue Hill, 2 miles north of Medina, Delaware County, Pennsylvania. Long, thin spindles of albitic plagioclase (approx. $Mi_4Ab_{90}An_3Cn_3$) in hyalophane (approx. $Or_{76}Ab_{11}An_1Cn_{12}$). Note the small blebs of "secondary" origin giving a "grained" appearance to the whole. (Kindness of Dr. S. G. Gordon.) (1437)

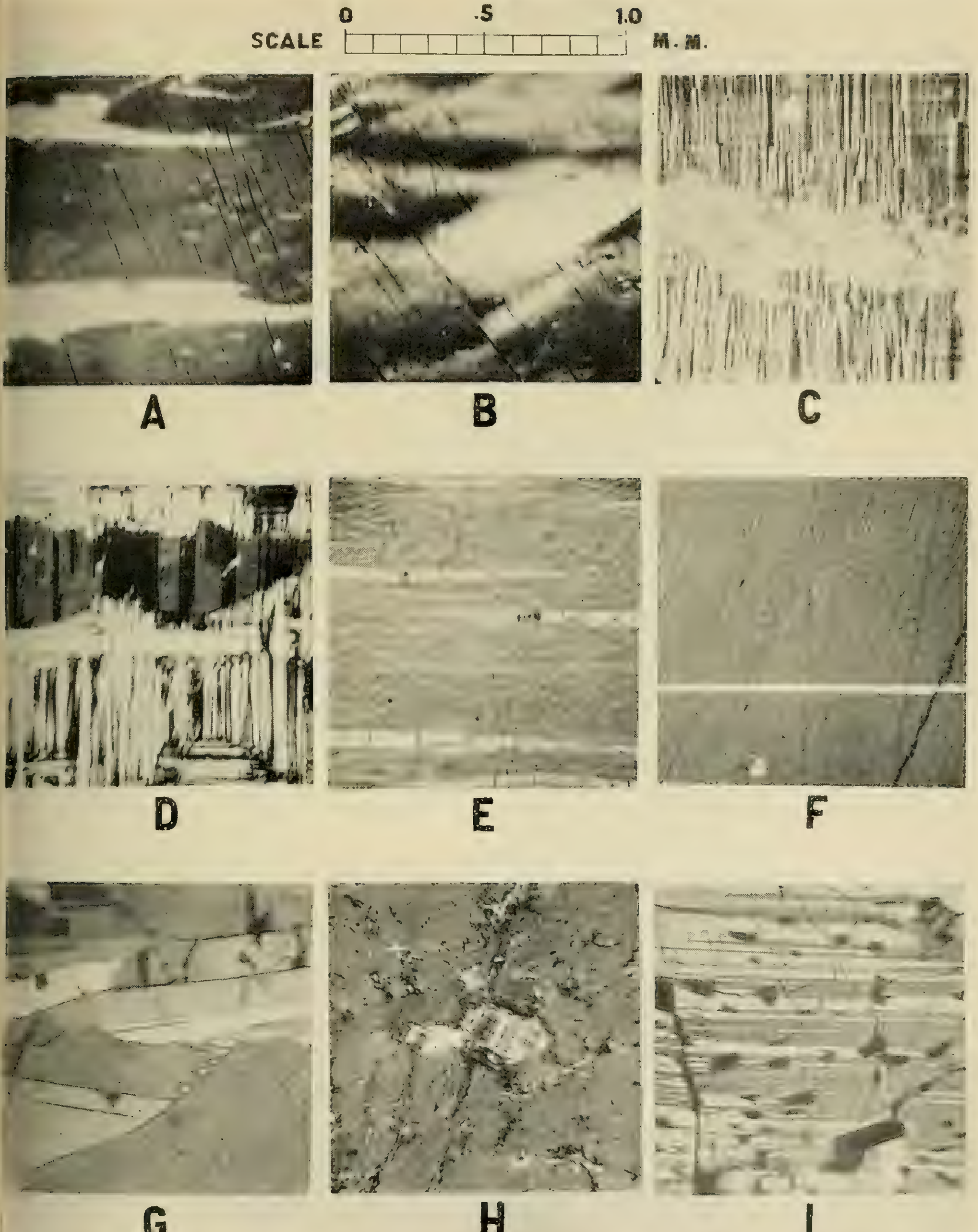
F. Bytownite ($Mi_{2.0}Ab_{24.7}An_{73.3}$), Crystal Bay, Minnesota. The white bar is a twinning striation, otherwise the slide is devoid of twinning of any kind. Unless extinction angles or indices of refraction are noted it may well be mistaken for "orthoclase." (969)

G. Albite (approx. $Or_7Ab_{83}An_2Ne_8$) from Kragerö, Norway. Possibly the so-called "barbierite," showing coarse albite twinning. (Kindness of Dr. Olaf Andersen.) (1123)

H. Potash oligoclase, Risör, Norway ($Mi_{7.30}Ab_{73.65}An_{19.05}$), showing bleb of soda microcline (center) in slightly weathered untwinned oligoclase. (Kindness of Dr. Olaf Andersen.) (1122 *b*)

I. Granite feldspar, Adirondacks, Ausable Quadrangle near Ausable Forks, Essex County, New York (quarry near Stickney Bridge), consisting of potash feldspar blebs (approximately $Or_{85}Ab_5An_{10}$), dark areas, in Labradorite ($Mi_5Ab_{40}An_{55}$), striated plagioclase. (1096)

Plate II



small specimen received from Professor Barbier verified his optical determinations, but was returned before any chemical tests could be made. Dr. Olaf Andersen sent the writer a specimen labeled "albite" from Kragerö, Norway. This proved to be a peculiar feldspar (see Plate II, *G*). The indices are: alpha, 1.527; beta, 1.534; gamma, 1.537. These agree well for albite, $Ab_{98}An_2$. The extinction angles, however, failed to be commensurate with the

TABLE IV

SECOND RECAST OF BARBIERITE

	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	Total
Percentage.........	67.00	19.12	0.78	1.15	11.74	99.79
Mol ratio..........	1.112	.1870	.0139	.0122	.1894	....
K-feldspar.........	.0732	.0122	....	.0122	....	6.82
Na-feldspar........	.9840	.1580	....	....	.1580	83.11
Ca-feldspar........	.0278	.0139	.1039	....	....	3.31
Nephelite..........	.0628	.0314	....	....	.0314	8.93
Total.........	1.1118	.2155	.0139	.0122	.1894	102.17
Excess........	.0002	....	....	....	....	....
Deficiency.....	....	.0285	....	....	....	....
Percentage.....	.01	2.92	....	....	....	....

values of the indices. (001) : 1.4°;[1] (010) : 23.9°.[1] Thus it is quite possible that this is a nephelite bearing albite of the following approximate composition: $Or_7Ab_{83}An_2Ne_8$.

Foerstner's[2] investigations of the anorthoclases of the island of Pantelleria took the form of measuring their physical properties at various temperatures. He reached the conclusion that the potash-soda feldspars constituted *two* series, one asymmetric and the other monosymmetric. "Both of these [systems] under consideration show isodimorphism of the corresponding alkali silicates [$KAlSi_3O_8$ and $NaAlSi_3O_8$], first emphasized by Professor P. Groth, one 'molecule' being in stable and the other in labile[3] equilibrium. A

[1] Determined by using the biquartz wedge after Wright.

[2] H. Foerstner, "Über künstliche physikalische Veränderungen der Feldspäte von Pantelleria," *Zeitschr. f. Kryst.*, IX (1884), 333.

[3] It seems to the writer that "metastable" is preferable to "labile." See G. H. Gulliver, *Metallic Alloys*, 1913, 164–65. Also Miers and Isaac, *Jour. Chem. Soc.*, LXXXIX (1906), 413; *Proc. Roy. Soc.*, LXXIX, A (1907), 322; *Phil. Trans.*, CCIX, A (1909), 337.

mixture of both of them, accordingly, tends to adjust itself to the final static molecular state. Inability to attain this [condition] is caused by the overpowering influence of the additional isomorphous constituents."[1]

He shows that through the proper physical means this molecular overbalance can be broken up. He believed that it was perfectly possible to change triclinic feldspar into a monoclinic form by heating, and vice versa by cooling. This can be explained, as Mäkinen points out, by dimorphism and not by Groth's theory of polysymmetry. It must be remembered, however, that most of these physical properties are measured upon the cold specimen, and such observations may or may not apply to heated feldspar.

Here the matter of the dimorphism (and isomerism) of both the potash and soda feldspars rests.

Thermal diagrams and dimorphism.—Various investigators have suggested diagrams that indicate the possible dimorphism of $KAlSi_3O_8$. It is not necessary to discuss them all in detail. A satisfactory conception can be obtained by examining the accompanying diagrams (Fig. 1, Part II). These have been modified more or less in detail by the writer to bring them up to date; the main facts, however, remain.

Warren[2] has modified Vogt's original diagram to indicate the inversion of orthoclase into microcline. This is shown by the line *Cp* in Figure 1. It will be seen that it interrupts the solubility line *iN* in that microcline is less able to dissolve the soda feldspar component. The consequences of this, as Warren points out, are that many perthitic intergrowths are due to exsolution caused by the decrease in solubility of the soda phase in the potash component on its inversion. According to the diagram orthoclase and microcline cannot exist together in equilibrium over any range in temperature. Whether they can or cannot exist in this manner in nature it is impossible at present to say. Although Mäkinen[3] says that "no examples [are] found in natural feldspars" the writer in Part I listed an adu-

[1] H. Foerstner, *op. cit.*, p. 348.

[2] C. H. Warren, "A Quantitative Study of Certain Perthitic Feldspars," *Proc. Amer. Acad. Arts and Sci.*, LI (No. 3, 1915), 127, 154.

[3] *Op. cit.*, p. 149.

laria from Eggerhorn, Switzerland,[1] as "in the process of inverting from soda orthoclase to soda microcline" in view of the two sets of extinction angles and the variability of the microclinic twinning. Since that time several additional feldspars have been found that apparently exist in this transitional stage, although it is quite likely that such feldspars are metastable systems and not in equilibrium. Foerstner[2] has already suggested the possibility that certain anorthoclases are mixtures of the two series, "monoclinic" and "triclinic," and hence are representatives of "transitional" feldspars.

Thus it may be seen that there are two general ideas expressed by these diagrams. First, that of Warren, where the dimorphism is shown by a single line (Cp), and second, by Mäkinen by an area, a spherical triangle, FGH.

As the writer understands Warren's diagram, the solubility line iN holds when orthoclase does not invert (transform) to microcline. In the event of this change in modification, ipy_5N graphically indicates the decrease in solubility. These two possibilities are combined in a single diagram which may be confusing, unless this duality is kept in mind.

Harker[3] has given a diagram showing changes during cooling in a binary system where limited solubility prevails in the solid state and where one component inverts to a lower temperature form. While Harker did not state in definite terms that this illustrated the behavior of the potash-soda series of feldspars, he believed that it can be so regarded if a single line conception is entertained.

The suggestion of Mäkinen, that the transformation of orthoclase to microcline should be indicated on the diagram by an area, means that within a restricted range of temperature and composition, FGH, both orthoclase and microcline can be in equilibrium. H is an "invariant" point, in the language of the phase rule. This means that any change in temperature or composition or both destroys one of the phases. At H there are three phases present: H as soda orthoclase[4], H as soda microcline,[5] and I as potash albite.[6] The phase

[1] Specimen 989.

[2] *Op. cit.*, pp. 348, 188. [3] *Op. cit.*, p. 256, Fig. 83. [4] $Or_{69}Ab_{31}$. [5] $Mi_{69}Ab_{31}$.

[6] K-feldspar$_{11}$Ab$_{89}$. The noncommittal "K-feldspar" is used because it is not definitely known whether it is microcline or orthoclase.

rule states that one of the phases must of necessity be destroyed[1] which, according to the diagram, is impossible. This absurdity can be appreciated by an illustration. Consider the solid substances *H* and *I* as already mentioned, composed of three phases, soda orthoclase, soda microcline, and potash albite. Let the temperature be lowered 5 degrees and the composition be enriched by 1 per cent of $KAlSi_3O_8$, shifting the point to a position within the triangle *FGH*. Within this area orthoclase and microcline are in equilibrium. Now one of the phases must disappear, according to the rule. Potash albite should then vanish. But how? Apparently the diagram is in error. Perhaps the error is not really in the diagram after all, but rather in our insistence that all three phases *are in equilibrium* with each other. The diagram would be correct if it was stated to be an "unstable equilibrium" diagram. A thoroughly satisfactory diagram showing the dimorphism of the potash component would have the inversion boundary indicated by a line, and not by an area.

The real point is that we should not fit the feldspars to the diagram, but rather the diagram to the feldspars. Thus if Mäkinen's diagram is for plutonic feldspars, indicating cooling slowly under quiet conditions, we can expect that orthoclase can form and remain unchanged during the cooling of the rock, until jarred or subjected to variable pressure. Then it would pass from the potential microcline form into the stable modification microcline, not all at once probably, but by slow degrees, and hence orthoclase and microcline would exist side by side during the time interval of change. A diagram to express this would obviously be an unstable equilibrium diagram. Mäkinen's diagram is incorrect if perfect equilibrium is insisted upon, but it is very likely relatively correct if unstable conditions are to be represented graphically.

The writer through thermal treatment[2] has been led to suspect that the transition range, in which both orthoclasic and microclinic feldspars exist, is to be represented by a transition line with the

[1] The mathematical expression of the phase rule is $C-P+2=F$, where C=number of components, P the number of phases and F number of degrees of freedom. $C=2$. ($KAlSi_3O_8$ and $NaAlSi_3O_8$.) $P=3$ (as said above). Hence $2-3+2=1$. But we said that H is invariant which should give us a zero for an answer. (All this provided equilibrium prevailed.) We can conclude therefore that the diagram is in error.

[2] Experiments were conducted in the laboratories of the department of physics of the University of Rochester in platinum furnaces. Temperature was measured by platinum-iridium pyrometers of high quality.

$KAlSi_3O_8$ end higher than the soda rich ranges. This can be expressed in other words: the temperature range of inversion is lowered by an increase of soda. This is contrary to Mäkinen's diagram. It is not the purpose here to emphasize this point unduly, but merely to suggest where additional light is desired.

Let us briefly examine the diagram of Marc.[1] Here the dimorphism of both components of the system is indicated. He says (in translation), "Whether the transition point *i* (Fig. 1 in Part II) is situated above the melting point *b* has not been determined." The temperature scale as originally given is only approximate and consequently the writer has taken the liberty of shifting it to more nearly match that of Mäkinen.

X-RAY ANALYSIS

Kozu, Endo, Suzuki, and Seto[2] have investigated specimens of adularia, moonstone, and sanidine with the X-ray spectroscope. Their discoveries are important. The adularia ($Or_{88.3}$ $Ab_{9.3}$ $An_{2.4}$) from St. Gottard was shown to have a single space-lattice which was unaltered by heating over the whole temperature range of its crystalline state. A Ceylon moonstone ($Or_{74.4}$ $Ab_{23.1}$ $An_{2.5}$), however, exhibited two space lattices[3] at all temperatures below 700° C. Above this temperature it became a single space-lattice system. A thin section of a moonstone from Ceylon[4] which may have been similar or identical with the material studied by Kozu et al., proved to be a cryptoperthite, microscopically agreeing well with the results of X-ray analysis. A moonstone from Korea ($Or_{61.9}$ $Ab_{32.7}$ $An_{5.4}$), a feldspar still richer in soda, exhibited the same property but the temperature of the passage from a two-space lattice structure to a single-space lattice system was about 500° C. In contrast to the latter, a sanidine from the Eifel ($Or_{76.9}$ $Ab_{21.8}$ $An_{1.3}$) behaved as though it was a homogeneous solid solution of orthoclase and "barbierite." "As is well known, however, the Eifel sanidine has a peculiar optic property, easily variable optic axial angle with the change in temperature, that is, an unstable molecular structure with respect to temperature. Though we cannot enter into the discussion of this

[1] Robert Marc, *Chemische Gleichgewichtslehre,* 1911, p. 102.

[2] *Science Reports of Tohoku University* (Sendai, Japan), Series III, Vol. I, No. 1.

[3] As shown by two sets of Laue photographs. A cryptoperthite.

[4] Purchased from Ward's Natural Science Establishment. Specimen No. 1394.

in detail at present, it is obvious that further researches would bring us very interesting and important results. . . . ."[1] It is evidently a metastable solid solution under molecular stress, tending to develop into a two-phase system, but prevented from doing so by the high viscosity which is characteristic of the solid state.

The investigation of these moonstones calls our attention to the feldspars called cryptoperthites. Such feldspars represent transitional stages from the unstable solid solution, anorthoclase, to stable perthite and which without much doubt can be classified as solid colloids—almost isocolloids. The passage from anorthoclase to perthite is through the intermediate stages of crypto-and microperthite; from a "molecular" dispersed system through a colloidal dispersed state to a mechanical intergrowth.

While X-ray analysis throws much-needed light upon internal arrangement of the atoms the question of the degree of equilibrium attained by each given specimen is still unsolved, for these minerals have different origins and, as already pointed out, furnish data for different diagrams. Here is a problem for the future, in the solution of which the Tohoku University investigators should have a prominent share.

In addition to their X-ray analyses these Japanese workers have conducted a series of thermal experiments that agree in large measure with the results obtained by Vogt, Dittler, Johannsson, Vegard, Watts, Douglas, Mäkinen, and the writer.[2]

[1] S. Kozu and K. Seto, "Sanidine from the Eifel," *Science Repts., Tohoku Univ.* (Sendai, Japan), Ser. III, Vol. I, No. 1, p. 27.

[2] J. H. L. Vogt, "Physikalish-chemische Gesetze der Krystallisationsfolge in Eruptivgesteinen," *Tsch. Min. Petro. Mitt.*, XXIV (1905), XXV (1906), and XXVII (1908); E. Dittler, "Die Schmelzpunktskurve von Kalinatronfeldspaten," *ibid.*, XXXI (1912), 513; "Über die Darstellung kalihaltiger basischer Plagioklase," *Min. und Petro.* Neue Folge., XXIX (1910), 273–333; "Über das Verhalten des Orthoklase zu Andesin und Celsian über seine Stabilität in künstlichen Schmelzen," *Tsch. Min. Petro. Mitt.*, XXX (1911), 118–27; H. E. Johansson, "Om fältspaternas sammansättning och bildings forhållanden," *Diese Zeitschr.*, XXVII (1905), 338; Vegard, "Die Konstitution der Mischkrystalle," *Phys. Zeitschr.*, XVIII (No. 15, 1917), 93–96; A. C. Watts, "The Feldspars of the New England and North Appalachian States," *U.S. Bur. Mines Bull. 92*, 1916; J. A. Douglas, "On Changes of Physical Constants in Minerals [by heating]," *Quar. Jour. Geol. Soc.*, LXIII (1907), 159; Eero Mäkinen, "Über die Alkalifeldspäte," *Geol. Foren. Förhandl.*, XXXIX (1917), H. 2. For synthesis see F. W. Clarke, "Data of Geochemistry," *U.S. Geol. Surv. Bull. 606*, 364–67.

In the course of thermal studies of his own the writer has found that a convenient test for the development of glass (or leucite) on the margins of crushed fragments which have been subjected to high temperature is to measure the indices of refraction by the immersion method,[1] using the Becké test, with monochromatic light. This will reveal the thinnest possible shell of glass upon an unaltered core.

Such thermal experiments would suggest that the liquidus and solidus curves of some of the diagrams should not be so flat as those of Mäkinen, etc. Mäkinen has shown that a perthite ($Mi_{68}Ab_{30}An_2$) when heated to 1200° C.[2] exhibited incipient fusion and says (in translation): "The perthite albite is almost entirely melted and contained abundant blebs [bubbles]. The microcline [phase] was so much altered that the extinction angle on the (001) face in the proximity of the melted albite amounts to 9-10° and as for the rest it amounts to 15° as the maximum." Here Mäkinen had the chance of drawing a valuable conclusion. Consultation of the optical constants of the feldspars would have at once suggested that anorthoclase had been developed by re-solution. The writer has satisfied himself through actual thermal experiments that the long heating of the microcline-microperthite (hypoperthite) from Verona, Ontario, Canada (approximately $Mi_{41}Ab_{58}Ab_1$),[3] at 1000° C. produced anorthoclase of approximately the same composition as the sum of the two phases of the original.

[*To be continued*]

A PRELIMINARY REPORT ON THE MICROSCOPY OF ANTHRACITE COAL

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INTRODUCTION

In connection with petrographic studies during the winter of 1921–22, the authors became interested in the microscopic characteristics of anthracite coal. A review of the literature, however, revealed the fact that very little had been accomplished in this field. The reason appeared to be the inability to prepare specimens that would show their microscopic structures. An investigation was therefore begun which had as its purpose the treatment of anthracite so that its microscopic features could be easily discerned. The results of the method finally adopted are revealed in the accompanying photographs which show some of the most conspicuous structures observed. While no attempt is made at this time to classify definitely the organic forms, some tentative conclusions nevertheless seem warranted from the observations thus far made.

The coal used in connection with this investigation came from the Northern, Western Middle, and Southern Fields of the Pennsylvania anthracite region. Specimens from the Buck Mountain, Primrose, and Mammoth beds from each field were studied.

METHODS ADOPTED

After considerable experimentation with thin sections and various chemical reagents, with unsatisfactory results, the method herein described was developed. It consists briefly of obtaining a polished surface on the coal and etching with heat. Although pieces of various sizes and shapes are used, blocks of coal about two centimeters square take the most uniform polish and are large enough to be handled with ease. Larger pieces can be used provided that one has the equipment for polishing them, and such may be

desirable when one wishes to study some particular form which extends for some distance through the coal. The microscopic examination of a large surface, however, is very fatiguing. Furthermore, one may easily miss important forms or spend hours re-locating minute structures.

Small blocks are therefore cut from the coal by means of an ordinary hacksaw. Two surfaces, one parallel to the bedding and one at right angles to it, are ground to planes. All sharp edges are beveled slightly to prevent pieces from breaking off and scratching during the subsequent smoothing. These plane surfaces are then polished to remove saw marks and scratches.

Different ways of obtaining a polish were tried. The method which gave the quickest and most satisfactory results, however, consisted of first grinding on a revolving iron lap with medium-sized carborundum powder and water; next smoothing by hand on plate glass, using one-minute tripoli powder and water; and finally polishing by rubbing in one direction on a novaculite honestone with a paste of rouge and water. This paste should be fairly thick, for the best polish is obtained when the specimen is rubbed until the paste is almost dry and the coal sticks to the hone. A few brisk rubs on dry chamois with rouge, or on broadcloth with diamantine, remove all water stains and leave a very high gloss. Chromic oxide may be substituted for rouge with equally good results. On account of its green color it possesses the added advantage of not being confused with the reddish oxide of iron resulting from the oxidation of iron compounds in the etched coal.

The polished surface obtained in the above way, although not entirely free from scratches, suffices for good results. When the few remaining scratches interfere, they are removed by rubbing on a dry hone without rouge and finally polishing further with diamantine on a flat block covered with broadcloth. The hone, when used dry, has a tendency to become covered with a dark gumlike substance due to the adherence of fine particles of coal. This is overcome by rubbing down from time to time with a second hone, using a lather of soap and water. Not only is the gumlike coating removed but the surface of the hone is also kept flat by this treatment.

The polished specimen is finally placed in a drying oven over a Bunsen burner and heated from room temperature to about 220 degrees Centigrade, to remove moisture, and to obviate splitting of the surface due to sudden heating during the etching process. After this temperature has been maintained for about an hour, the specimen is removed with the forceps and the polished surface immediately brought to a red heat by means of the oxidizing blow-pipe flame. A differential oxidation is thus produced which reveals the structure in relief without destroying the polish to any great extent. The surface should appear only slightly foggy owing to an almost imperceptible film of ash.

The duller layers in the coal etch more rapidly than the bright ones, making it necessary at times to warm and etch repeatedly in order to bring out the greatest detail. Those varieties which show little lamination and are made up almost wholly of jetty bright coal must be etched in a little different way to overcome splitting of the surface. Instead of the oven a sand bath is used. The coal is immersed in clean dry sand with only the polished surface exposed. The bath is placed over a battery of four Bunsen burners and brought to a temperature of 300 degrees Centigrade. This temperature is maintained for about half an hour when the polished surface is heated in place to a bright red heat with a blast lamp, using a rather large blue flame which is played slowly back and forth over the surface. A little experience will demonstrate the advisability of re-etching to further define partially hidden structure.

Various attempts were also made to utilize oxygen in etching. A stream of cold oxygen was directed on the surface of a specimen heated to about 400° Centigrade, but only served to keep the surface cool and prevent etching. Warm oxygen used in the same way gave no better results. Oxygen at very high temperatures was not used in this way. Etching is produced, however, by heating polished specimens in an atmosphere of hot oxygen under slight pressure. In the latter case the coal is placed in a piece of glass combustion tubing about two feet long. Oxygen is passed through water in a wash bottle and into the combustion tube through a rubber stopper

in the upper end. In the lower end is placed a two-hole rubber stopper through which a thermometer is inserted. The temperature is raised to 250° Centigrade by heating the tube with a Bunsen burner just beyond the coal, between it and the intake. The action is continued until the polish begins to grow dim. Great care must be exercised to prevent the surface of the coal from coking. The forms revealed by this method of treatment are not as sharply defined as those produced by direct heating and since it requires more time, care, and apparatus, it is not recommended where direct heating can be used. The only advantage is that the surface remains flat and therefore shows some structures in coal which might otherwise be largely reduced to fragments by direct heating.

The etched coal is finally studied with the metallographic microscope, using vertical illumination from a carbon arc. A good working objective is one of medium power giving a magnification of about 250 diameters. A clean-cut image can be obtained up to a magnification of 1,000 diameters. In all cases the eye can discern finer details than are shown in the photographs.

The method as outlined, except for a modification of the etching process, has been successfully applied to bituminous coal and cannel coal. The polished cannel coal was held for a few moments in the oxidizing Bunsen flame without being previously heated in the oven. Good results can probably be obtained with carbonaceous shale and other materials of similar nature.

GENERAL RESULTS

A preliminary examination of the specimens of anthracite from the different fields shows that all varieties are composed of laminae of different luster, texture, and thickness. Brilliant jet black layers alternate with glossy black or gray bands in which are imbedded thin sheets of dull material resembling charcoal. The brilliant black layers vary in thickness from a few microns to many centimeters. The glossy gray bands are thicker than the jet black ones although, on close inspection, they are shown to contain many thin sheets of the brilliant black coal and thin sheets of dull material. The brilliant layers are more compact than the duller ones and

FIG. 1.—(×170) crosswise to the bedding, from Pennsylvania anthracite. Shows spore exines. The markings on the spores are probably lines of dehiscence. This group of spore exines was found in the duller layers.

FIG. 2.—Section (×170) crosswise to the bedding, from Pennsylvania anthracite. Shows large, wrinkled spore exines found in the duller layers.

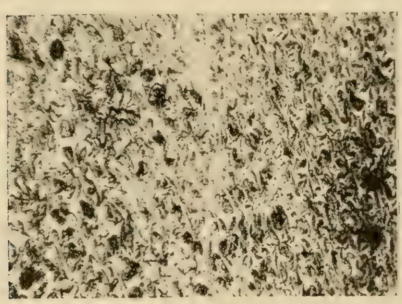

FIG. 3.—Section (×125) crosswise to the bedding, from Pennsylvania anthracite, showing crushed and warped cells, observed in a zone surrounding a knot of almost structureless charcoal.

possess a more perfect conchoidal fracture. Where they are thick, the broken surface often shows rounded or oval fracture forms. Although the above distinctions hold true for most of the anthracite, some varieties appear at first glance to be composed wholly of the brilliant coal, revealing their various laminae only on careful examination.

Mineral charcoal was quite abundant in almost all the coal examined. Cleaving coal parallel to the bedding exposed charcoal-covered surfaces in every specimen which showed distinct lamination. On the other hand the varieties which were poorly laminated and almost uniform in luster contained very little charcoal.

In addition to the thin sheets of charcoal so commonly found in the bedding planes, one finds occasional large fragments which cross several of the horizontal layers. These large pieces of charcoal are of particular interest because of the fact that they show in most cases perfect cells almost entirely devoid of filling. The cell walls are thicker than those of the original wood and appear to be lined with a bright jet black layer which permits good photographs by reflected light. All

the large lumps of charcoal examined have the structure of conifer wood. Rings of growth, medullary rays, and bordered pits are distinctly shown.

Ordinary commercial charcoal differs from the mineral charcoal in no essential detail when examined with the microscope. This condition seems to argue against regarding the charcoal as the product of forest fires, for it seems probable that the cells would either have been filled with the putrefaction product solutions during subsequent immersion in the bog, or crushed under the pressure of overlying material.

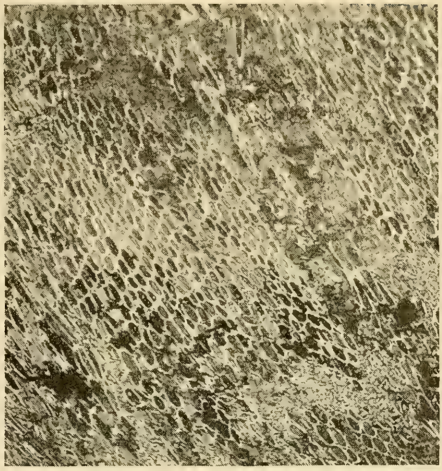

FIG. 4.—Section (×50) parallel to the bedding of the Forge split of the Mammoth bed from Nanticoke, Pennsylvania. A section of wood showing original cell laminae. The remarkable preservation of these cells may be due in part to the silicious filling shown by the gray areas within the cell walls, although some of the cells are filled with black, lusterless carbonaceous material.

The brilliant layers of the coals examined show, under the microscope, either no structure or a preponderance of wood fiber and wood cells. In the glossy duller layers are found spore exines, former resinous materials, apparent vascular bundles, cuticles, wood fiber, cell laminae, and other forms not yet identified. The thin dull black layers usually show wood fiber and wood cells either well preserved or crushed to an almost structureless mass. Further microscopic details can be most advantageously described in the legends of the microphotography.

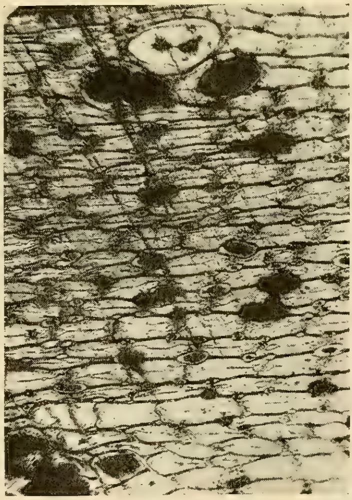

FIG. 5.—Section (×126) crosswise to the bedding and oblique to an apparent stem in anthracite from Pennsylvania. This section is of particular interest because it is in the brilliant jetty coal and not in the duller layers where such forms are usually found.

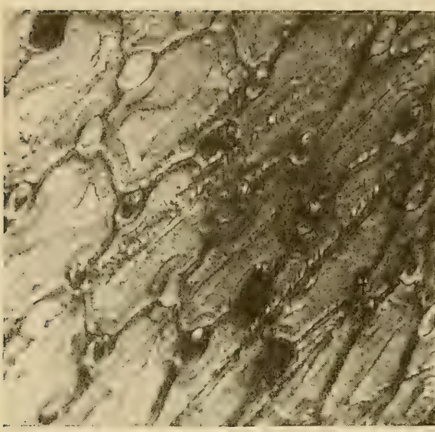

FIG. 6.—A part of Fig. 5 (×500) showing the great detail revealed by the method of treatment described in this paper. Note the delicate dumbbell-shaped membrane with the cells and the elliptical markings surrounding the small knots along the cells walls.

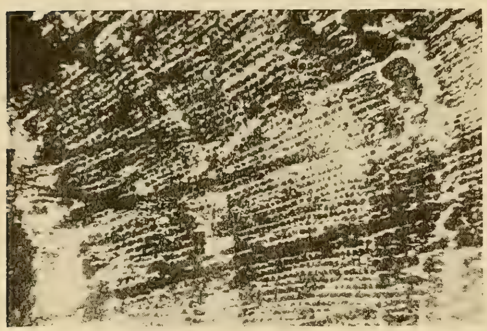

FIG. 7.—Cross section (×83) of a charcoal stem of coniferous wood found in anthracite from coal measures around Minersville, Pennsylvania. Note the well-defined medullary rays and annual rings. The rather thick cell walls are composed almost entirely of bright, jetty material making possible this photograph by reflected light. The black spots within the cell walls are holes.

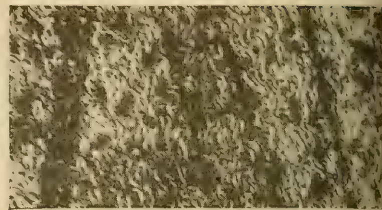

FIG. 8.—Section (×118) crosswise to the bedding of coal from the Primrose bed, William Penn colliery. This section through the duller layers shows wood fiber much contorted.

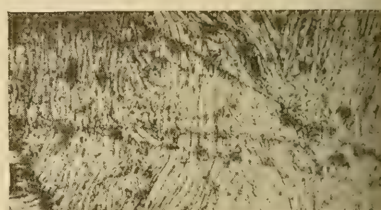

FIG. 9.—Section (×118) crosswise to the bedding of the Primrose bed showing less flattened wood fiber.

FIG. 10.—Section (×124) crosswise to the bedding, from Pennsylvania Anthracite. This section through the duller layers shows a somewhat macerated wood fragment containing round bodies which are probably vessels formerly filled with resin or gum.

Almost all the specimens studied show remarkably smooth and regular vertical joints at right angles to the bedding planes. Some of the less distinctly laminated varieties possess, in addition to the regular vertical joints, bright slickensided surfaces at low angles to the bedding. Those varieties which show distinct lamination can be cleaved easily parallel to the bedding while the more massive types possess almost no cleavage.

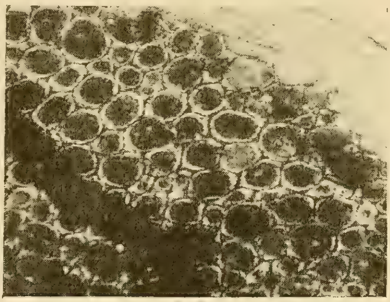

FIG. 11.—Section ($\times$125) crosswise to the bedding of coal representing the Forge split of the Mammoth from Nanticoke, Pennsylvania. Shows cells of xylem or phloem of a vascular bundle. This is a section through a dull knot. Some of the cells are partly filled with small grains of pyrite which do not show in the photograph. The black centers are dull carbonaceous material.

Aside from the more splendent luster, anthracite is shown, from the above description, to possess all the essential megascopic characteristics of bituminous coal; in addition it shows the same types of organisms under the microscope; and further, these organisms are apparently no more distorted than those of the bituminous coal.

The authors expect to make a detailed study of some of the best-known anthracite seams of Pennsylvania. It is hoped that this study will lead to a better knowledge of the factors involved in the origin of anthracite. From the observations thus far made, it seems highly probable, also, that the various beds can be correlated through the identification of dominant plant types and through other microscopic characteristics, although this will obviously involve a great deal of study and observation both in the laboratory and in the field.

The writers wish to thank Mr. John H. Stoll and Mr. R. H. Christ, of the Bethlehem Steel Company, the officials of the Susquehanna Collieries Company, Professor H. B. Pulsifer, of the metallurgy department of Lehigh University, Doctor B. L. Miller, of the geology department of Lehigh University, David White, of the United States Geological Survey, for their kindly co-operation.

GEOLOGY OF THE PHILIPSBURG REGION OF QUEBEC WITH NOTES ON CORRELATIONS WITHIN THE BEEKMANTOWN

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OUTLINE

INTRODUCTION

The region along the northeastern shore of Lake Champlain, which in this paper will be termed "the Philipsburg region" because the area especially under consideration extends northeast and southwest from the town of Philipsburg, Quebec, has been studied by many geologists, Canadian and American. The rocks of this vicinity occupy a stratigraphic position in that zone of uncertainty on the Cambro-Ordovician boundary, which at the present time is an important question of controversy. For this reason they have been studied by the writer with the utmost care, with the hope that more facts might be gained concerning the events which transpired between the deposition of the Potsdam and the Chazy beds in the Champlain Valley.

Although the rocks of the Philipsburg region may be said to be well known, they are at present far from being well understood.

The complexity induced by a complicated system of close folding and overthrust faulting has paved the way for varying interpretations of structure, while a dearth of fossils has resulted in erroneous correlations based mainly on lithological similarities and an insufficient study of what few fossil remains have been obtained. The writer spent eleven weeks in this area during the summer of 1922. This time was largely devoted to a thorough search of all available and likely outcrops for fossils. The great bulk of the rock was barren, but determinable fossils were found at seven different horizons; at one in great abundance. Several new forms were discovered and will be described at a later date. It has been thought advisable to present in some detail the structural and lithological peculiarities of the strata in this region, because in some cases the correlations suggested in this paper must rest largely on inorganic evidence. Since the proof or disproof of a widespread Ozarkian system must rest on the complete understanding of such sections as that of the Philipsburg region, such a detailed presentation seems justified. The purpose of this paper is to present a summary of the evidence, from field and faunal studies, that no Ozarkian rocks are present in this area; that no great diastrophic or faunal breaks, which are the accepted basis for the separation of geological systems, occur in the northeastern part of the Champlain Valley. If the correlations suggested here survive the test of detailed study in other regions to the west and southwest of Lake Champlain, it must follow that not only at Philipsburg, but throughout the Champlain Valley, deposition was not interrupted by any great break until the end of Beekmantown times.

STRUCTURAL RELATIONSHIPS IN THE PHILIPSBURG SERIES

The rocks of the Philipsburg series occupy a position in northern Vermont and southern Quebec between the east shore of Mississquoi Bay and the valley of the Rock River, two miles to the east (Fig. 1). Their southern extremity can be seen in an outcrop along the line of the Vermont Central Railroad about 500 yards northeast of the mouth of Rock River, Vermont. The strike here is N. 28° E. Following this direction southwestwardly across the lowland of the Rock River, we next find rocks of a different char-

acter which contain Black River fossils in abundance. Similarly following in the direction of the dip, which is S. 21° E., we find the section terminated one mile to the east by a ridge of quartzitic rock

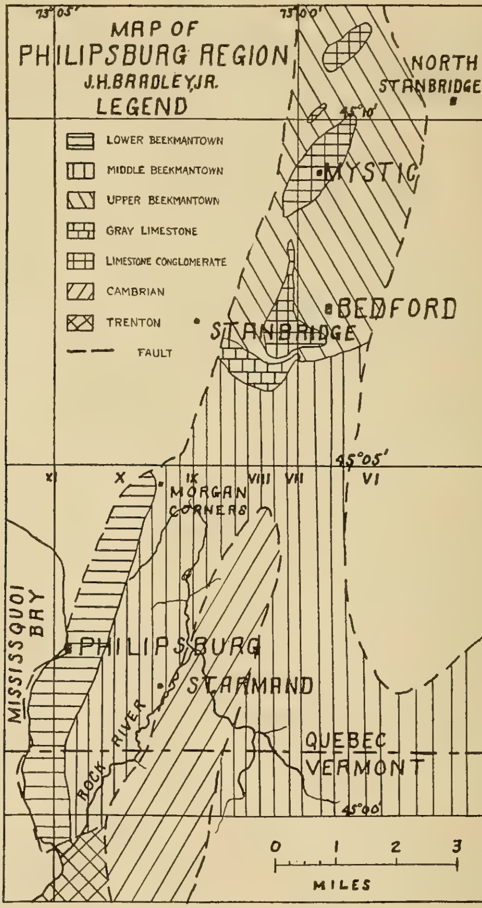

FIG. 1

from which Upper Cambrian fossils have long been known. The faulting which terminated the Beekmantown section to south and east will be discussed later.

Following northward along the strike from the southern extension of the series, we can trace the lower bed two miles across the

international boundary into Quebec to Philipsburg two miles beyond. From Philipsburg the strike, which maintains a northeasterly direction, carries us away from the lake. In this direction the series can be traced through Morgan's Corners (formerly Blood's Corners) to the village of Bedford, where higher strata come in, and beyond to Mystic. The northernmost outcrop of the highest bed which is traceable, occurs about two miles north of Mystic on the twenty-second lot of range six, Stanbridge, Quebec.

Using this outcrop as an arbitrary northern limit of the series, the area under discussion is roughly fifteen miles long. The width varies from about a mile and a half on the south and north to about three and a half miles in the middle. On the east, west, and south the section is truncated by faults. To the north the prevailing limestone gives way to slates whose structure and stratigraphy are as yet very little understood.

In 1863 the intricacies of the geology of the Philipsburg region were made known by Logan in his admirable report on the geology of Canada.[1] This work was done in great detail and with great accuracy. The general division of the section into four parts on the basis of lithology seems a good one for the sake of discussion, and in this paper the writer will adhere to Logan's Divisions A, B, C, and D. It must be remembered, however, that these divisions, although marked lithologic units, are not necessarily stratigraphic or structural units. This fact will be made clearer in the subsequent discussion. Logan's section, in descending order, is briefly as follows:

	Feet
D	
3. Grey and black striped slates interstratified with thin beds of black limestone and limestone conglomerate	1,500
2. Black and greenish argillaceous slates with patches of limestone conglomerate and bands of magnesian slates	1,000
1. Black limestone conglomerates, composed chiefly of the ruins of thick bedded limestones of division C	300
	2,800
C	
2. Black slates and thin-bedded black limestones, toward the top imperfectly seen	170
1. Black and dark grey compact pure massive limestones with a few bands of dove grey	150
	320

[1] Sir William Logan, *Geology of Canada*, 1863, pp. 175–280; 844–54.

B

	Feet
5. Black limestones, some of them massive, weathering bluish-grey; interstratified toward the bottom with black and dark grey yellow weathering magnesian beds	350
4. Black slaty thin-bedded nodular limestones with beds of purer limestone toward the base	300
3. Dark bluish-grey thin-bedded nodular limestone with some magnesian slate	150
2. Dark grey and black limestone, some of the beds magnesian	120
1. White and dove grey pure limestones, with some yellow-weathering magnesian bands	120
	1,040

A

	Feet
3. Reddish-grey brown weathering dolomites, and black dolomites with some thin-bedded black limestones	200
2. White and dove grey pure compact limestones	100
1. Dark grey and yellowish-white dolomites, weathering grey and yellowish-brown	400
	700

Total thickness..........4,800 feet

DIVISION A

The lowest members of the series are well exposed at the town of Philipsburg and follow the shore of Lake Champlain south to the Vermont-Quebec boundary. At this place the rocks rise in cliffs which form an almost perpendicular wall at the water's edge, and are known locally as the "High Rocks." These cliffs continue southward with diminishing height almost to Rock Bay, two miles south of the boundary. Although these beds can be followed northeastward from Philipsburg for about eight miles, it is the "High Rocks" exposure which sheds most light upon their structural arrangement. At this point overthrust and reverse faulting, and close folding are common phenomena. The evidence of this exposure is that the thrusting force acted normal to the strike with the overthrust from the southeast. The close folding so clearly displayed here is typical of folding throughout the entire Philipsburg area. The pressure came probably after the beds had been lithified, picking up the thinner beds into folds and overthrusting or reverse faulting the thicker beds. Two minor overthrust faults can be seen in this lake shore exposure and two minor reverse faults

as well as several partly overturned synclines and anticlines—all in limestone of the lower part of the grayer facies of Logan's A1.

It might be well to mention at once that one important characteristic of the entire series is that the average outcrop gives little or no evidence of any folding whatsoever, so that it is particularly difficult and often impossible to tell when the same stratum has been repeated in a close fold. Most of the beds—if they may be called beds—are thick, and the trend of the rocks, although it can usually be ascertained in general, is not easily measured with exactness because the bedding is so obscure in many places. For this reason and for reasons to appear later in connection with a discussion of minor folding, an accurate measurement of thickness is well-nigh impossible.

The lowest beds of A1 rest upon crumpled beds of black slates interstratified with thin bedded, brownish weathering calcareous strata. These slates occupy a narrow strip of lake shore from Philipsburg south. They show marked signs of deformation, but in no outcrop do they appear to have suffered folding contemporaneously with the overlying limestones. Although no fossils appear to substantiate the general belief that the slates are of Trenton age, neither is there paleontological proof that they belong to the older age of the overlying rocks. The structural evidence, on the other hand, though scanty, would argue for Logan's interpretation, that the limestones were thrust over the slates. The folding and faulting just mentioned in the overlying A1 beds can be explained best by a thrusting force from the southeast. The same force if strong enough, could have acted on the entire mass of limestone as a competent block, thrusting it to west and north.

Although in the large, the lake shore exposure of the strata comprising A1 bears out the general evidence of neighboring regions regarding the direction of the thrusting force, there is clear evidence locally of overthrusts from the northwest. These thrusts directly opposed to the direction of the main thrusting force can be explained on the basis of initial dip or a vertical shifting of the horizon of major thrust.[1]

[1] Bailey Willis, "Mechanics of Appalachian Structure," *U.S. Geol. Surv., Ann. Rept. 13*, Part 2 (1892).

On the shore of Missisquoi Bay, three-fourths of a mile north of the international boundary, a group of thin-bedded siliceous strata underlie the massive, apparently unbedded limestone of A1. The dip is gently to the east and the beds are conglomeratic in part, with well-rounded pebbles as large as eight inches across. These strata are associated in places with very thin-bedded black shale. The entire thickness is less than ten feet and at the top the strata grade into the calcareous rock. These beds are interesting in view of Walcott's statement[1] that "a small outcrop of Potsdam sandstone, with characteristic fossils, subjacent to the limestone of the Calciferous" occurs on the lake shore near Philipsburg.

These siliceous beds are the only strata similar to the outcrop described by Walcott that a week's search revealed to the writer. Following north along the shore, in one place three-quarters of a mile south of Philipsburg, a marked unconformity was found between the massive overlying limestones of A1 and the narrow layers of sandstone which overlie the Champlain fault. Here the sandstone dips to the east as it does farther south. The overlying limestones, in this place apparently thin-bedded, meet the underlying sandstones almost at right angle, and then after bending into a small anticline, resume their easterly dip parallel to that of the sandstone. It is the opinion of the writer that this local difference in the attitude of the strata is due purely to differential folding in the two beds rather than to causes implying uplift and erosion.

A1 proper is composed of two lithologically different limestones, which maintain their distinctive qualities in most of the places where the members can be observed. The folded rocks mentioned above are of granular nature, largely limestone, but chemically impure with magnesium and mechanically impure with detrital quartz. A few brown weathering, highly magnesian beds are noticeable. These strata are the lowest of the series and predominantly grey in color, weathering grey and brown; they will be spoken of here as the grey facies of A1.

The beds of the grey facies are somewhat thinner than the apparently overlying yellowish grey and buff (weathering yellow brown) granular limestone. These beds will be referred to as the buff facies

[1] Charles D. Walcott, *Bull. Geol. Soc. Am.*, Vol. I, p. 512.

of A1. It is likely that as a general rule the compressive forces effected folding in the grey facies, and fracture in the buff facies. The most southerly extension of the "high rocks" exposure on the shore south of the boundary exposes well the buff facies of A1. There is a slight valley between these cliffs and those of the grey facies to the north. Although the bedding in the buff facies in most places is almost impossible to determine, the impression given is that they stand almost vertically. If this is the case and if the buff facies really overlies the grey, the buff beds have been faulted down and upturned in the general deformation which closely folded the underlying grey strata.

About 250 yards east from the lake at the international boundary the yellowish white, brown weathering magnesian limestones of the buff facies come in on top of the grey. In one place one-eighth mile south of the boundary, this line of contact was traced in a continuous outcrop for 100 yards. At the southern extremity of this outcrop the yellow white limestone appeared to be standing on end, in very much the same attitude that it appears to be standing in the escarpment three-fourths of a mile south of the boundary on the lake shore. In this place it would seem that the yellow white limestone is above and younger than the grey limestone. Following the boundary east to the valley parallel to the lake which is occupied by the Philipsburg–Highgate Springs road, the limestone of the grey and buff facies seems to become interbedded and finally grades into a pure compact dove grey limestone. The outcrops of these beds are conspicuous because they weather smooth and very often light grey to white. These beds belong to Logan's A2. Beds of A1 and A2 can be followed from the Boundary northeast by almost uninterrupted exposures to Morgan's Corners. Here a well defined line of fault is beautifully shown north of the road running east to Bedford.

A3 follows A2 first with reddish grey granular beds of limestone and these in turn by black limestone. In an unpublished letter, Dr. G. A. Young, of the Geological Survey of Canada, has recognized these two quite distinct phases of Logan's A3. He named these members A3*a* and A3*b*. Since the integrity of these divisions is maintained in the faulted zone at Morgan's Corners, it is important

to distinguish which part of A3 is being dealt with. The lithology of the two members is well described by Logan.

Following the black beds of A3*b* northeastward, the strike is seen to curve slowly to the east. At Morgan's Corners they are disrupted and turned up on end. Back of the schoolhouse at this place, beds of A3*b* are seen to strike due east-west and to dip northward gently. Following this strike eastward, the beds shortly assume the vertical position. A little east of the schoolhouse the black A3*b* beds have in contact with them to the south, the light grey to white, crystalline to granular, beds of lower members. The inference would be that the pressure which bent the rocks to the east along their strike across range 10 of St. Armand, finally caused the beds to break at this point. The rocks to the north of the fault were upthrown and turned vertically.

Following east, the black beds of A3*b* fold over an anticlinal axis associated with beds of A2. This fact leads to the conclusion that the faulting at Morgan's Corners was a result of pressure which died out in the direction of the anticline. If this is true, the dislocation in A3 and A2 at Morgan's Corners cannot be of great extent.

Scarcity of fossils in Division A.—It is unfortunate that in A1, 2, and 3, with an assigned thickness of 700 feet, organic remains should be so rare. A careful search failed to discover in this entire thickness any remains of undoubted organic origin. Some few gastropods in a poor state of preservation and determinable only on the broadest generic lines, were found by former investigators. The scarcity of fossils has made the correlation of these lower beds exceedingly difficult. It is clearly evident from field observation that the A and B series are unbroken structurally. We have no evidence of uplift and erosion between A and B. Likewise, there is no evidence that A and B are separated by a fault. As a matter of fact, the separation of these beds into A and B on a structural basis, is wholly arbitrary, and a more logical arrangement would be to include A and B in the same series. On the other hand, some of the strata in B are highly fossiliferous. These fossiliferous beds of St. Armand and Stanbridge are the only reliable means of obtaining any light on the age of the rocks in Division A, so that in the absence of any break in deposition between A and B, the writer

has correlated A partly on the basis of its own lithological makeup, but largely on the faunal evidence of the overlying B strata.

It is possible that even if organisms were living in the waters which gave rise to the A beds, clastic deposition was so slow that the calcareous shells were dissolved and reprecipitated as normal lime rock before they could be buried and preserved as fossils. It is a striking fact that the few fossils found in A were but faint shadows of the original organisms. The state of preservation of these fossils strongly suggests that dissolution was active before the rocks were lithified, and only those individuals whose shells were thick and resistent, succeeded in being preserved.

Strike faults and Minor folds.—At the international boundary the beds of A can be followed down the dip with almost no concealment. To the casual observer, the beds would seem to be dipping to the southeast at a gentle and fairly constant angle. The rock is peculiarly massive and unbedded, and it is only with careful study that the true dip can be ascertained. In the section cited, between the lake shore and the road, the A1 beds are turned up practically on edge, possibly overturned in places. The pure, dove-grey beds of A2 show no good criteria for correct measurement of dip, except that they conform generally to the normal southeast dip of the whole series. A3, on the other hand, being made up of less pure, reddish-grey granular limestone, with magnesian beds, and shaly black limestones, shows the effect of compressive forces. At the international boundary the A3 beds, near their contact with those of A2, fold under a synclinal axis. One bed of A3*a* is prominently exposed where the strike can be followed without break around the nose of the trough. Other beds of A3*a*, which would not bend, are seen in a much faulted condition nearby, lying at various angles. This undulation in A3 appears to have been effected by a thrust from the southeast, causing a steeper dip on the east limb of the syncline and a gentler dip on the west limb.[1]

The folding in A1 on the lake shore was probably localized in horizons of the more thinly bedded strata of the grey facies. With the exception of these folds, seen and traceable on the surface, the mass of A as a whole is distorted more by faulting than folding.

[1] Sir William Logan, *op. cit.*, 1863, pp. 846, 847. See also Fig. 2.

Although it cannot be definitely proved by field evidence, it is probable that the province line section just described is crossed by transverse dislocations, which are suggested by the terraced nature of the outcrops. The occasional upturned dip of the lower strata of A can be explained in this way.

DIVISION B

By far the most important rocks of the Philipsburg region are those of the B series, because it is in them that structural features can be best traced, and from them the most fossils evidence was obtained. These rocks follow the beds of A and are well exposed in a syncline just west of St. Armand Station (Fig. 2). From here they strike across the township of St. Armand into Stanbridge, where they are succeeded conformably, about one mile south of

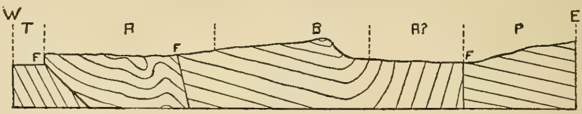

FIG. 2.—Diagrammatic section along the International Boundary, eastward from Mississquoi Bay. P, Potsdam; A, Lower Beekmantown; B, Middle Beekmantown; T, Trenton; F, fault. Horizontal scale, ½ inch = 1 mile; vertical scale exaggerated.

Bedford, by the strata of the C series. The higher beds can be traced from the vicinity of St. Armand village continuously to the region where they are succeeded by the beds of C. These strata are well described by Logan.

DIVISION C

Fossils were collected near the axis of the syncline from the massive black limestone of B5 about one mile north of St. Armand station on the Stanbridge road. The dip in the rocks at the roadside is 2°–4° S.W. About 300 yards west, an outcrop shows a dip of 10° S.E., thus marking the synclinal structure. From the outcrop on the road, several fragments of thick-shelled trilobites, and brachiopods were found. In a somewhat lower bed on the western flank of the syncline, surface indications of Maclurea ponderosa and

other large gastropods were common. The writer followed the B5 beds north to lots 6 and 7 of range 7, where the massive beds of C come in. In C1, practically the same fauna of thick-shelled forms was collected. This faunal similarity between B5 and C1 is important because it corroborates the structural evidence that C directly overlies B. There is no evidence of uplift and erosion.

The massive beds of C, although limited in their exposure, are striking because of their light-colored weathered surfaces and the peculiar smoothly rounded outcrops. They have been quarried for lime extensively in the past and are known as the "panther" rocks locally. The large coiled gastropods conspicuously outlined on their surfaces probably are the cause of this section's having been assigned to the Chazy, because of a remote similarity between Maclurea ponderosa and M. magna.

The existence of Logan's C2 between these conspicuous beds of C1 and the conglomerate of D has been doubted by some because of the nearness of outcrops of C1 to D1 on the sixth and seventh lots of the seventh and eighth ranges of Stanbridge. Although D1 is very poorly exposed, the present writer found indications of black slates in several places underlying the first conglomerate band of D. On lot seven, range seven, a small outcrop of slate was found within stone's throw of C1 on the south and D1 to the north. It is probable, however, that Logan's thickness of 170 feet is too great. C2 is probably nearer to 50 feet in thickness. The dips of C1 in this region show the same syniclinal arrangement noticed at St. Armand station. The slope of the trough becomes more gentle to the northeast.

DIVISION D

The massive black limestone conglomerates of D1 outcrop along the line of the Canadian Pacific Railway on range eight Stanbridge between Stanbridge station and Bedford. The strike here is N.65 E. Conglomeratic bands can be followed from this point northeastward to lot 22 range six Stanbridge. Towards the bottom, D1 appears to be in places a massive non-conglomeratic limestone. Three-quarters of a mile on the wagon road east of Stanbridge station,

well-rounded pebbles of sandstone occur with the black limestone pebbles. This indicates that in this place at least we have a normal conglomerate.

Following the elliptical outcrops of D1 to the road about one mile north of Mystic, which runs from Notre Dame to North Stanbridge, the conglomerate can be seen in outcrops which might be called typical. True bedding is absent. The rock is composed largely of elongate fragments of dark grey and black limestone weathering grey. The matrix, likewise of black granular limestone, weathers dark brown and black, thus showing the shape of the pebbles to good advantage. In some places the pebbles are scarcer and the rock has the aspect of a massive black limestone. In other places the rock is made up almost entirely of fragments. The pebbles range from small round masses one-half inch across to pieces one to two feet in diameter. Associated with these rounder fragments are the more common elongate pieces which range from one-half inch to two feet in length and from one-half to one and a half inches in width. These long fragments have a general alignment normal to the strike and clearly show that they are the broken, reworked slabs of a former thin-bedded black limestone whose fragments have not been transported very far.

Southwest along the strike, the conglomerate was found to contain, in places, a few irregular masses of black slate. In places a nodular condition was seen, as if mud had been deposited with the lime. At Mystic Station good outcrops of conglomerate show bedding. Some of the strata, particularly those with an abundance of vein calcite, were only slightly conglomeratic, and were chiefly composed of massive black limestone. A little farther south fossils were found in the matrix.

To obtain a complete picture of this conglomerate we must study the outcrops on lot two and twenty-two, range six. In one place the fragments have a peculiarly brecciated appearance. Pieces of dove grey pure limestone compose the greater part of the beds. The paste is of darker material, in places slaty and largely calcareous. In one place above the more brecciated zone, a bed of massive, partly broken grey limestone occurs. No paste seems to be mixed in with this limestone; the broken fragments appear to have been

recemented by lime dissolved from themselves. From this rock a good collection of fossils was obtained.

Half a mile south of Bedford a much sheared black limestone dipping to the northwest is overlain by a band of conglomerate apparently dipping to the southeast. Much shearing and crumpling occurs at the contact. A thrust fault of minor magnitude probably occurred here. This band of conglomerate is probably of a different horizon from the one described above and belongs to Logan's D3. Many large angular and sub-angular fragments occur and the material is entirely unassorted as to size.

Logan's conclusion that the lower strata of D were formed from the breaking down of the massive beds of C1 is not substantiated by fossil evidence. Nowhere in D has the thick-shelled gastropod fauna of C1 been found. In fact, gastropods are conspicuously absent from the fauna from D. Likewise the lithology of the conglomerates indicates that originally the strata of D were predominantly very weak and thin bedded. There is no evidence of any thin bedding in C1.

Although the section from D1 upward is in need of revision, particularly the great thickness of slate which occupy the spaces between the ridges of more resistent limestone conglomerate, a few facts are clearly present which throw light on the genesis of D. The intercalation of thin dolomitic beds with much of the slate, the great abundance of slate, as well as the presence of shallow water organisms in the paste of the conglomerate indicate a shallow-water origin. The general absence of rounding in the fragments of the conglomerate and their general allignment gainsay transportation and point to deformation of the unconsolidated beds in situ. This deformation was probably due to the same forces which formed the synclines and anticlines in the more massive underlying beds. The sub-angular appearance of the fragments argues for a submergence and prompt recementation of the broken beds.

If the thickness of D is anywhere near the 2,800 feet assigned to it by Logan, deposition must have been interrupted many times in the course of formation. The entire thickness is strikingly thin bedded wherever bedding planes have not been obliterated by subsequent folding and recementation.

SIMILARITY OF PHILIPSBURG AND EAST SHOREHAM SECTION

Brainerd and Seely divided the Beekmantown rocks exposed at East Shoreham, Vermont as follows:[1]

DIVISION E

Fine-grained magnesian limestone in beds one or two feet in thickness, weathering drab, yellowish or brown. Occasionally pure limestone layers occur, which are fossiliferous, and rarely thin layers of slate.

Thickness............470 ft.

DIVISION D

4. Blue limestone in thin beds, separated from each other by very thin tough slaty layers, whose weathered edges protrude in undulating lines. The limestone often appears to be a conglomerate, the small enclosed pebbles being somewhat angular and arenaceous. (100 ft.)

3. Sandy limestone in thin beds, weathering on the edges in horizontal ridges one or two inches apart, giving to the escarpments a peculiar banded appearance. A few thin beds of limestone are interstratified with the siliceous limestone. (120 ft.)

2. Drab and brown magnesian limestone, containing several beds of tough limestone toward the middle. (75 ft.)

1. Blue limestone in beds one to two feet thick, breaking with a flinty fracture; often with considerable dolomitic matter intermixed, giving the weathered surface a rough, curdled appearance; becoming more and more interstratified with calciferous sandstone in thin layers, which frequently weather to a friable ochreous rotten-stone. (80 ft.)

Thickness............375 ft.

DIVISION C

4. Magnesian limestone like No. 2, frequently containing patches of black chert (120 ft.)

3. Sandstones, sometimes pure and firm, but usually calciferous or dolomitic (70 ft.)

2. Magnesian limestone in thick beds, weathering drab. (100 ft.)

1. Grey, thin-bedded, fine-grained, calciferous sandstone, on the edges often weathering in fine lines, forty or fifty to the inch, and resembling close-grained wood. Weathered fragments are frequently riddled with small holes, called Scolithus minutus by Mr. Wing. (60 ft.)

Thickness............350 ft.

DIVISION B

Dove colored limestone, intermingled with light grey dolomite, in massive beds; in some places for a thickness of twelve or fifteen feet no planes of

[1] Brainerd and Seely, *Bull. Am. Mus. Nat. Hist.*, Vol. III, 1890–91.

stratification are discernible. In the lower beds, and in those just above the middle the dolomite predominates; the middle and upper beds are nearly pure limestone; other beds show on their weathered surface raised reticulating lines of grey dolomite.

Thickness............295 ft.

DIVISION A

Dark iron grey magnesian limestone, usually in beds one or two feet in thickness, more or less siliceous, in some beds even approaching a sandstone. Nodules of white quartz are frequently seen in the upper layers and near the top, large irregular masses of black chert, which, when the calcareous matter is dissolved out by a long exposure, often appears fibrous or scoriaceous.

Thickness............310 ft.
Total thickness of section............1,800 ft.

This section is perhaps the best known and most complete exposure of Beekmantown rock in the western part of the Champlain Valley. Certain faunal and lithological zones, well-marked in this section, are clearly present in the Philipsburg section, sufficient, it is believed, for exact correlations. These correlations appear to obtain throughout the Champlain Valley whenever good sections of Beekmantown strata occur. In view of this fact, it would seem that the term Beekmantown should no longer be used in a vague, indefinite sense, pertaining in general to any strata above the Potsdam and below the unconformity at the base of the Chazy. It is the opinion of the writer that the terms Lower, Middle and Upper Beekmantown, can be used in a definite, formational sense, and he therefore proposes those names for the Beekmantown in the Champlain Valley, to be applied in the following manner.

LOWER BEEKMANTOWN

Unfortunately the lower part of the Philipsburg section is cut off by a fault, while that of the East Shoreham section rests in uncertain relationship on the underlying so-called Potsdam sandstone. Nevertheless it is apparent that Brainerd and Seely's Divisions A, B, and C at East Shoreham are lithologically similar to Logan's Divisions A1, A2, A3 at Philipsburg. Dark iron grey magnesian limestone, usually in beds one or two feet in thickness, more or less siliceous, in some beds even approaching a sandstone, characterize the lowest members of both sections. Nodules of

white quartz are frequently seen in the upper layers of A at East Shoreham and A1 at Philipsburg. Near the top of this member at both localities, large irregular masses of impure black chert occur. The most striking similarity in the two members is the apparently complete lack of fossil remains. The thicknesses given for the respective members are 310 feet and 400 feet. The former probably represents the entire thickness at East Shoreham. Logan's estimate, on the other hand, cannot give indication of the true thickness because of the overthrust fault cutting off the base of the section at Philipsburg, and because of faulting and close folding which probably occur down the dip of the member, but which are not clearly shown in available outcrops. It is probable, however, that the Beekmantown strata thicken to the northeast.

Overlying the lower zone in both the eastern and western territory is pure, predominantly dove-colored limestone. The thickness for this bed is given as 295 feet at East Shoreham. This estimate includes transition beds above and below, which are dolomitic. The middle, however, is nearly pure limestone, and therefore a distinct horizon in a section that is largely dolomite. This bed is represented at Philipsburg by Logan's Division A2, estimated at 100 feet and lithologically identical with the pure limestone facies of the middle of Division B at East Shoreham. In both sections the Lower Beekmantown is terminated by a series of red-grey to black dolomites, magnesian limestones and sandstones from 200 to 350 feet in thickness.

The uppermost members of the Lower Beekmantown on both eastern and western shores of Lake Champlain are, like the lower members, quite devoid of fossils. It is interesting to note that the only fossils reported from either region were derived from the middle, pure grey limestone horizon; at East Shoreham *Orthoceras primigenium Vanux.*, *Cryptozoön steeli*, and an indeterminate gastropod of the Holopea type; and at Philipsburg, indistinct forms resembling the genera *Pleurotomaria* and *Holopea* have been observed. Although it would be dangerous to draw conclusions concerning the exact age of these lower members on such a scant faunal basis, it is true that what fossils do occur are prophetic of a later Ordovician fauna and not reminiscent of any known Upper Cambrian forms.

In 1910, Ulrich and Cushing[1] in studying the age and relations of the Little Falls dolomite, which they correlate with Division A and the part of B below the dove-grey limestone horizon at East Shoreham, found evidence of an important break between the Little Falls dolomite and the Tribes Hill limestone above. Commencing at Ticonderoga on Lake Champlain and passing from there to Whitehall, 20 miles south, thence to Saratoga, 35 miles farther south-southwest from Whitehall, thence into the Mohawk valley, 20 miles southwest of Saratoga, and from there west to Little Falls, Middleville, and Newport, about 40 miles farther, they found evidence of this important unconformity. They state that the Tribes Hill and Little Falls formations seem unconformable everywhere in New York and they make this unconformity the dividing line between the proposed Ozarkic and the Beekmantown.

Since the Division A and B at East Shoreham, which Ulrich and Cushing have correlated with the New York Little Falls dolomite and Tribes Hill limestone respectively, can be correlated so closely on lithological grounds with Logan's Division A1 and A2 at Philipsburg, an unconformity might be expected between these two members. It is true that an abrupt change in the deposition did occur, but there appears to be no evidence of a diastrophic movement of importance. It is the opinion of the writer that the line between the Upper Cambrian and the Beekmantown in the Champlain Valley cannot as yet be definitely drawn. With more careful study of available sections, it becomes clearer that no important break occurred until the end of the Beekmantown. It is generally agreed that the stratigraphic relations of the Potsdam to the overlying Theresa and Little Falls dolomite indicate a sequence of sedimentation interrupted by no important break.

Wherever the line is drawn in the Champlain Valley, it does not seem logical on any ground to separate the Little Falls dolomite (Division A1) from the pure dove-colored limestone of Division A2 (Tribes Hill) at Philipsburg. Although faunal evidence is almost entirely lacking, it is apparent that the dolomites above and below the Tribes Hill limestone were deposited under essentially

[1] E. O. Ulrich and H. P. Cushing, *New York State Mus., Bull. 140* (1910), pp. 97–140.

the same conditions and separated from the Tribes Hill by no time break that could have greater than diastemic value.

The transition beds of Logan's A3 at Philipsburg, made up largely of reddish grey, brown weathering dolomites, succeeded by black massive dolomites, appear quite unfossiliferous. They are clearly represented at East Shoreham by Division C of Brainerd and Seely. In both the localities these beds are characterized by large quantities of wind blown sand and by an absence of fossils. In both localities, dark massive dolomites predominate at the top. Above these massive dolomites in both regions come rocks that carry diagnostic fossils and it is here that the line should be drawn between the Lower and Middle Beekmantown. In this brief discussion of the lower Beekmantown, it has not been the writer's intention to lay down any definite limitations. The present state of knowledge concerning these unfossiliferous and deformed rocks is still too incomplete to warrant a final correlation at this time. It has merely been the intention to point out the possibility of correlating the Lower Beekmantown east and west of the great Champlain fault and to suggest the inadvisability of inferring a great unconformity between the Philipsburg representatives of the Little Falls dolomite and the Tribes Hill limestone. Until fossils are found directly above and below the contact between Logan's Division A1 and A2 that prove a considerable break, the pure limestone of A2 must be considered to have been deposited, to be sure under special conditions, but in the same sea without intervening erosion directly subsequent to the formation of the impure dolomites of Division A1.

MIDDLE BEEKMANTOWN

The Middle Beekmantown at East Shoreham, Vermont, in which the writer proposes to include Brainerd and Seely's Divisions D1, D2, D3, D4, and E, rest with apparent structural conformity on the Lower Beekmantown. These Divisions can be correlated with the Middle Beekmantown at Philipsburg which includes Logan's Divisions B1, 2, 3, 4, and 5, and C1, on faunal and lithological grounds. Divisions B5 (upper part) and C1 are not represented at East Shoreham because of post-Beekmantown erosion, which removed all of the uppermost strata of the Middle Beekman-

town in this region. Here the Lower Chazy rests upon Division E, which is poorly represented but can be correlated with the lower part of Division B5 at Philipsburg. It is proposed here to include in the Middle Beekmantown all the strata predominantly of massive limestone and dolomite above the transition beds of the Lower Beekmantown, and below the shale and limestone conglomerate beds of the Upper Beekmantown. The advent of the Middle Beekmantown according to this division is sharply marked by the appearance of Ophileta complanata, and the close is equally sharply marked by the occurrence of a typical gastropod and cephalopod fauna. Like the Lower Beekmantown, the Middle is predominantly calcareous and dolomitic, while the Upper is characteristically shaly. It is perhaps not necessary here to enter upon a detailed comparison of the fauna of the Middle Beekmantown but merely to note the presence of a fauna assemblage in Divisions D5 and C1 at Philipsburg which is very similar to that found at the top of D1 at East Shoreham and known as the "Fort Cassin fauna." This marked zone of gastropods and cephalopods can serve as a general indication of the top of the Middle Beekmantown. Occupying approximately the same horizon in both localities and being dominated by thick-shelled representatives of such genera as *Murchisonia*, *Holopea*, *Cyrtoceras*, *Ecculiomphalus*, *Maclurea*, *Euomphalus*, *Raphistoma*, *Lophospira*, and *Orthoceras*, there is a marked similarity generically between specimens from the two provinces. Lithologically also the rocks are quite similar.

UPPER BEEKMANTOWN

It is proposed to include in the Upper Beekmantown all strata between the massive beds carrying the Fort Cassin fauna and the Chazy unconformity. In the Philipsburg region this consists of an unknown thickness of closely folded slate with intercallated lenses of limestone conglomerate. Near Mystic Station in one of these conglomerate outcrops, a fauna was collected by the writer which differed markedly from the typical Upper Beekmantown fauna of this region. It is possible that the Normanskill has been infolded at this locality. The Upper Beekmantown must, of necessity, be indefinite because of the erosion which followed its deposi-

tion. With the exception of the rocks at Stanbridge, it is not known to be represented in the Champlain Valley.

OTHER EXPOSURES OF BEEKMANTOWN IN THE CHAMPLAIN VALLEY

In a section at Fort Ticonderoga, New York, Brainerd and Seely report the presence of 75 feet of limestone with *Ophileta complanata* which they correlate with their Division D1. They report the presence of Division E with several undetermined species of *Euomphalus*, *Lituites*, *Cyrtoceras*, and *Orthoceras*. The strata between the top and bottom of the Middle Beekmantown are apparently unexposed here.

At Thompson's Point, 28 miles north of Fort Ticonderoga, Beekmantown strata occur, which probably belong to the Lower and Middle divisions.

At Providence Island, 24 miles north of Thompson's Point, New York, 236 feet of largely magnesium limestone occurs which probably belongs to the upper Middle Beekmantown.

The type section one-half mile north of Beekmantown station is very poorly exposed but carries the gastropod and cephalopod fauna which appears to mark the upper Middle Beekmantown.

Keith has recently brought to attention two formations from northern Vermont which may have close relationship with the Philipsburg strata to the north.[1] Three miles N.E. of Burlington occurs the Shelburne marble of 200 feet or more in thickness, which occupies the same stratigraphic position as the Highgate slate to the north. The Highgate slate has yielded fossils which Walcott and Schuchert have determined as Upper Cambrian. It is believed that the Shelburne marble is younger than the Highgate slate, and that the disappearance of the Highgate southward was more likely due to Upper Cambrian erosion than to non-deposition. The formation is almost entirely of white marble and may be contemporeaneous with the lowest beds (B1) of the Middle Beekmantown at Philipsburg, which have a similar marbleized facies.

The next succeeding formation described by Keith is the Williston limestone, which also outcrops near the town of Burlington.

[1] Arthur Keith, *Am. Jour. of Sci.*, Vol. V (1923), pp. 97–139.

This formation consists of light or dark blue limestone and marbleized quartzite and also dolomitic limestone. The prevailing blue color and thin bedding distinguishes it from the Shelburne. Fossils, although scarce, have been found. Some cephalopods and Ophileta-like gastropods were collected by Schuchert who assigned them to the "Saratogan." It is possible that this formation can be correlated with B2 and B3 at Philipsburg. The presence here of the trilobite *Lloydia saffordi*, which is highly characteristic of the Middle Beekmantown at Philipsburg, makes such correlation seem very plausible.

CONCLUSIONS

The purpose of this study of the Philipsburg section was to gain new knowledge concerning conditions during early Ordovician times. Although the fossil evidence to prove that the rocks of Division A belong to the same system as those of the overlying series is scant, nevertheless it at least in a small degree supports the testimony of field evidence. The field evidence indicates that no great break occurs until the end of the Beekmantown. It seems, therefore, just as logical to include the rocks of Division A with the Lower Beekmantown as to throw them into an older system for which, at least in this locality, there is no favoring evidence, either faunal or diastrophic. The divisions of the Beekmantown into Lower, Middle, and Upper, proposed in this paper, are believed by the writer to obtain generally in the Champlain Valley. To carry these correlations further is not advisable at this time because of the insufficiency of our knowledge.

FOLDS RESULTING FROM VERTICALLY ACTING FORCES[1]

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Because the most striking examples of folded rocks are to be seen in mountainous regions, folds are usually thought of as the visible results of compressional forces which act more or less parallel with the surface of the earth, the typical force of this kind being the compression effect of differential contraction of the lithosphere. But with the rapidly accumulating knowledge of more stable areas of the present land surface and especially from the increasing mass of data from deep well records, the importance of another kind of fold has come to be recognized. Although it seldom affects the present topography directly, this kind of fold is of great economic value because of its influence on the distribution and accumulation of gas, oil, and brines. Some of these folds are actually the direct result of a force acting vertically, others which also owe their origin to a vertical force seem to be rather the effect produced by components of this force acting more or less parallel with the beds. Most of the folds due to vertical forces occupy circular or oval areas, either singly or as groups. This shape or arrangement indicates an apical area which has been directly affected by an up-thrust or a down-throw.

At least five types may be recognized: domes or quaquaversal folds, radial linear folds, concentric terrace folds, linear terrace folds and monoclinal folds related to deep-seated faulting. Of these only one class, the domes or quaquaversal folds, is typically due to a force acting upward. As one would expect from the theoretical conception of the earth as a failing structure, most of the forces acted downward.

[1] Published with the consent of the State Geologist.

DOMES

These are the conspicuous folds resulting from an upward acting force, or from a set of forces whose resultant is active upward; as such they have been described for many years. They are often found to be genetically related to a bathylith, laccolith, or lava plug, but sometimes they are merely the locus of chemical action or of recrystallization which results in a great increase of volume within a limited area, as may be the case in the salt domes of the Gulf states whose origin is imperfectly understood. Less frequently, slight domes arise from the slumping of soft sediments. This is a phenomenon noted at times in present-day accumulations. Others are found in areas of different compressibility in the same layers of rock, especially near shore lines. How much difference in elevation the subsequent rock pressure might bring about upon such areas of unequal compressibility, cannot be estimated with the incomplete data at hand, but this may prove to be an important factor. In size, domes vary from great groups of mountains to small inconspicuous rises of ground a few acres in area.

RADIAL LINEAR FOLDS

Small folds are found near the periphery of large basin structures with their axes pointing toward the center of the basin. They are so broad and shallow that they are seldom recognized except when the section is plotted with vertical exaggeration. The dip of the limbs of these folds as they are found in the Michigan basin is well within the limit of initial dip of sediments, and the pitch of the axes is roughly parallel with the dip of the series as a whole. These folds, if known only for a single formation, would be considered to be due to peculiar conditions of deposition, but from the fact that they persist through many formations, and appear at points on every quadrant of the basin, they are obviously structures formed after consolidation. The uniformity of their distribution and their dimensions favor the idea, which was first proposed by Professor I. C. Russell,[1] that they are a result of the subsidence of a central area resulting in a crinkling of the peripheral portion just as an unfolded filter paper crinkles when pressed into a funnel.

[1] *Mich. Geol. Surv. Pub. 12*, Geol. Ser. 9, p. 207

It may be noted that this sort of fold would be the most imperfect "structure" possible for accumulating light liquids and gases, because the pitch would be uniform from the point of inception of folding to the outcrop and would be equal to, or greater than, the dip of the series as a whole.

Another explanation of the origin of these folds is that they are the result of unequal subsidence of portions of the periphery of the basin, but this explanation is less satisfactory in the case of the Michigan folds because such subsidence would be expected to produce faulting and folds of widely varying dimensions and unequal distribution.

An unequal distribution of soluble material such as rock salt near the periphery and its removal by solution, or the unequal solution of parts of a salt horizon, have been suggested to account for these folds. Considering only that area in southeastern Michigan where both the folding and the salt beds are best known, this explanation seems most reasonable, but as the folds are also known from other parts of the basin where the presence or absence of salt beds of sufficient thickness to produce the subsidence effect has not been proved, this, with the other explanations, must be only tentatively considered until more data are at hand. Whichever of the above hypotheses is favored, it will be noticed that the underlying cause is a vertically acting force, although under the subsidence hypothesis first mentioned, the force is supposed to be resolved into components acting tangentially around the periphery.

An examination and platting of well records already assembled by Lane[1] and Smith[2] results in the following pertinent suggestions.

1. The folds affect the latest rocks which are preserved—the Mississippian and Pennsylvanian.

2. There is an indication of gentle monoclines or terraces around the central basin which suggests two periods of subsidence.

3. These terraces separate the comparatively deep central area from the shallower peripheral area, and thus are suggestive of two distinct diastrophic areas.

[1] *Mich. Geol. Surv.*, Vol. V, 1881–93.

[2] *Mich. Geol. Surv. Pub. 14,* Geol. Series 11.

On the accompanying structure contour map (Fig. 1) several of these folds are indicated, but these are perhaps not the most typical examples because they are folds of larger dimensions, and

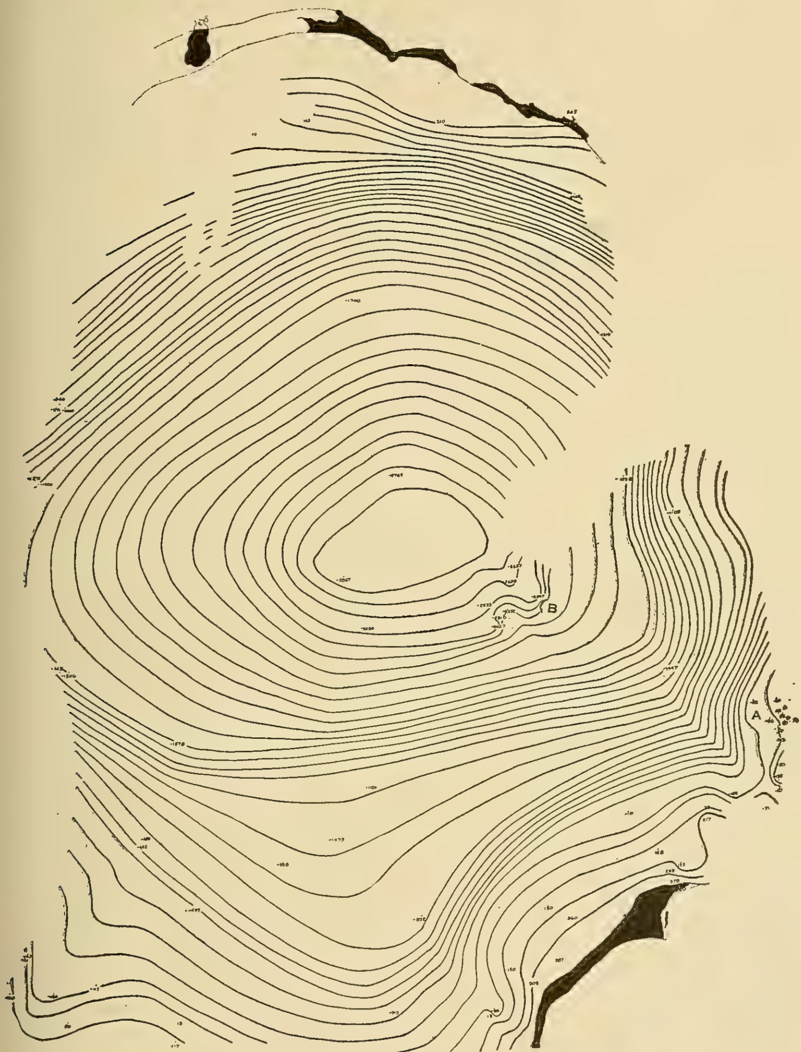

FIG. 1.—Structure contour map of Michigan. Contours drawn to the top of the Dundee (Onondaga-Hamilton). Areal distribution of Dundee, in outcrop and beneath the drift, in solid black. Contour interval 100 feet.

a lack of data makes it impossible to use a contour interval which would reveal the smaller and more common folds. Perhaps the most typical example shown is that of the St. Clair area (*A*). The shape and orientation of the fold in the Saginaw area (*B*) are typical, but the position of this fold is exceptional in that it lies near the center of the basin. The smoothness and regularity of the contours in the northwestern part of the state are due to a lack of data from deep wells. However, folds of the radial linear type are known from surface observations in the Northern Peninsula in the northwest quadrant of the basin. The location of one of these folds is shown in Figure 2 which is drawn to show the theoretical direction and extent of the radial linear folds of the basin.

The Michigan basin is exceptional in its lack of distortion by tangential forces, and therefore has a more conspicuous development of these folds, but it is believed that such folds are a feature to be sought for in every basin of persistently negative tendency. It is conceivable that under some conditions such folds might indicate favorable areas for prospecting for oil and gas. In case of unconformity, and with impervious sedimentary beds deposited over such folds after the deformation but before any great migration of contained fluids, this would certainly be true.

CONCENTRIC TERRACE FOLDS

A basin of persistently negative tendency, in which the only movements are slight and long continued, would be expected to develop terraces parallel to the margins of the basin and concentric around the central area, especially in the parts of the basin which are bordered by elements of a positive tendency. Such terraces have developed in the Michigan basin in the southern part, bordering the positive area which has been influenced by the Cincinnati anticline. These terraces which are shown in Figure 1 are found, by a comparative study of well records, to be developed at least as far down in the stratigraphic column as the Dundee (Onondaga-Hamilton). Such structures are important economically, and the significance of an understanding of their mode of origin and typical arrangement in regard to negative and positive areas, will be at once obvious to petroleum geologists.

FIG. 2.—The direction of the axes of folds as indicated by the results of deep drilling. Adapted from R. A. Smith.

LINEAR TERRACE FOLDS AND MONOCLINES BY FAULTING

These folds which exhibit similar features, and are well known from their development as oil producing areas, differ only in their

mode of origin. The linear terrace folds result from long continued gentle movements, and the monoclines produced by faulting are the expression of deep-seated faults which have decreased in effect toward the surface until, in the upper layers, there is distortion of the beds without actual rupture.

DEFINITIONS AND CONCLUSIONS

Domes or quaquaversal folds.—A. Inconspicuous folds usually small formed in undisturbed areas; the force secondary and small, vertical. The force may be (*a*) a chemical action or crystallization (salt domes), (*b*) the vertical component of lateral thrusts set up within the sediments, still soft, by the sudden accumulation of heavy sediments shoreward,[1] or (*c*) the unequal contraction during induration of sediments of differing compressibility. No topographic expression.

B. Conspicuous folds often large, the force coming from movements of magma. Domed mountains above bathyliths, laccoliths, lava plugs. Topographically striking.

Radial linear folds.—Small, radial, about basins of slight negative tendency; become apparent through drill records; dip of limbs well within the limit of initial dip; distinguished from folds due to unequal contraction during induration only by radial arrangement and persistence of fold to the basin floor contemporaneous with subsidence. Dominating force vertical and downward with resultants tangential in concentric areas giving compression effect parallel to periphery of basin.

Other explanations: unequal subsidence which would be more likely to cause faulting; unequal distribution or unequal solution in evenly distributed, easily soluble material such as salt.

Concentric terrace folds.—About basins of negative tendency. Caused by a failure of concentric areas, or by differences in compressibility of sediments. Simulate terraces due to thinning of sediments toward center of basin. Known only from comparison of deep borings. No topographic expression.

[1] See M. Albertson, *Mining and Metallurgy*, No. 170 (February, 1921), p. 38.

Linear terrace folds.—On long lines of movement in some cases apparent at surface. Not due to concealed faulting. Seldom have topographic expression.

Monoclines by faulting.—Simple monoclinal folds due to concealed faults. In some cases, with topographic expression.

This article has been written with the purpose of directing attention to the importance, economically, of the structures described. In the Michigan basin little encouragement is offered for their exploration, chiefly on account of the long continued exposure of this area to erosional forces, continuing as it apparently did from Pennsylvanian to Pleistocene time, thus keeping open the path for the escape of fluids along the axes of the radial linear folds and preventing the deposition of any impervious layers above them but with a different Tertiary or Mesozoic history areas of a similar nature would offer many interesting possibilities.

A PALEOZOIC ANGIOSPERM

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The morphology of Paleozoic plants is based for the most part upon the microscopic examination of concretions found in English, French, and German coal seams. These concretions are calcareous in England, and siliceous in France and Germany, and contain well-preserved tissues of plants. The matrix can be cut with a diamond saw, and the sections ground to transparency. The concretions are black, round, or irregular lumps, varying in size from an English walnut to a cocoanut. They appear in the upper part of the coal seam but never outside of it. In England they are called coal-balls and in Germany Torfdolomiten. The French use the English word. The value of a coal-ball for morphologic plant study depends not only upon the vegetable contents but also upon its purity from pyrite. The latter does little harm if it occurs in very small quantities, but observations are made impossible if the replacement of calcite or silica has progressed too far.

A great service to science, in making micropreparations from English coal-balls, has been rendered by the Lancashire and Ceshire Coal Research Association, better known as the Lomax Palaeo-Botanical laboratories of Bolton, England. There a wonderful technique has been developed by Mr. Joseph R. Lomax, who prepared the material for the classic investigations of W. C. Williamson, D. H. Scott, A. C. Seward, R. Kidston, F. W. Oliver, A. J. Maslen, and M. Benson. Almost all paleobotanic micropreparations in England and North America were supplied by the Lomax laboratories.

It seemed obvious that coal-balls should also be found in the extensive American coal basins, and a thorough search was made for them. The writer has collected good specimens in Illinois and Kentucky, and others were sent to him from Texas. It is true that

pure balls which contain only negligible quantities of pyrite are rare, but one collected by the Illinois State Geological Survey at Harrisburg, Illinois, O'Gara Mine Number 9, coal seam Number 5, satisfied all reasonable demands for purity. It was sectioned by Mr. J. H. Hoskins, of the Department of Botany at the University of Chicago, and described by him.[1]

The coal-ball in question contained an angiospermic stem of distinct monocotyledonous affinity. The stem portion was about 4 cm. long and 2 cm. in diameter. Throughout the cross-section (Fig. 1) are scattered numerous endarch collateral vascular bundles.

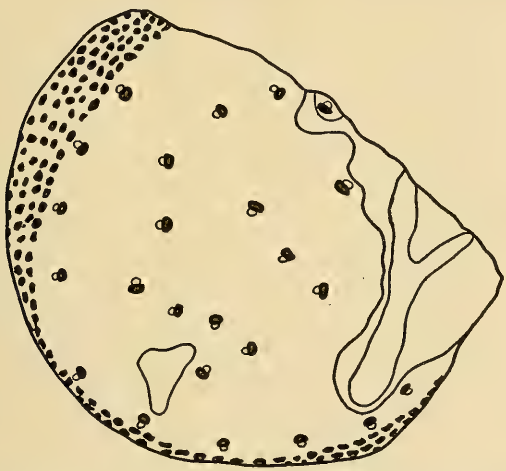

FIG. 1.—Diagram of cross-section of stem with peripheral groups of sclerenchymatous cells and scattered collateral bundles; xylem shown in black; rootlet has penetrated one side of stem (after Hoskins).

The phloem is oriented toward the periphery. The detail of a single bundle with phloem preserved is shown in Figure 2. Surrounding the xylem is a sheath of sclerenchymatous fibers, not extending completely around the bundle, nor present at the phloem side. Between this sheath and the heavy-walled xylem cells are usually thin-walled parenchyma. Throughout the cross-section are what were probably mucilage ducts. Placed near the periphery of the

[1] J. H. Hoskins, "A Paleozoic Angiosperm from an American Coal-ball," *Botanical Gazette*, Vol. LXXV (1923), pp. 390–97.

stem are numerous groups of small hexagonal and thick-walled sclerenchymatous cells, arranged in four or five irregular concentric rows. All these elements are surrounded by the solid parenchymatous tissue of the stem. The phloem was not preserved in most cases, but figure 2 shows it consisting entirely of thin-walled cells arranged

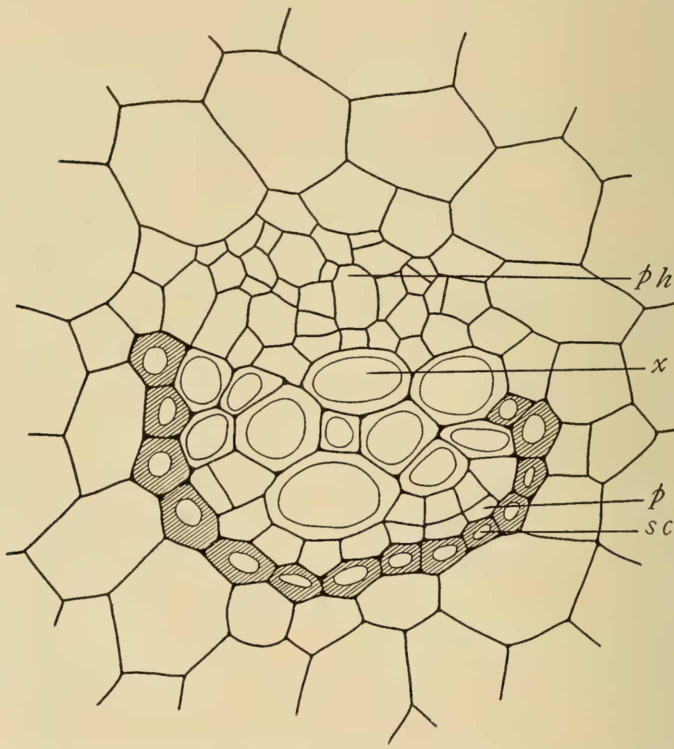

FIG. 2.—Cross-section of vascular bundle: *sc*, sheath; *x*, xylem; *ph*, phloem; *p*, parenchyma; ×350 (after Hoskins).

in such a way as to suggest large sieve tubes with companion cells. These morphological characters warrant the conclusion that the stem belonged to an angiospermic plant of the Monocotyledon branch. Although a comparative study with certain living Monocotyledons brings out striking similarities, a more definite statement as to the phylogenetic position of the fossil is postponed until other material can be secured. Therefore the generalized name "Angio-

spermophyton americanum" was chosen for the first-known Paleozoic plant of angiospermic affinity.

No traces of Angiosperms have previously been known below the Comanchian. Our coal-ball carries the highest plant type a long way back in the geologic time scale. Does it mean that we must greatly modify our conceptions of plant evolution? By no means. Only the lines of descent which seemed to converge in the Mesozoic take an aspect of greater parallelism which presupposes an immensely removed focus, just as the sun beams appear parallel to our eye and yet we know of their convergence. Succeeding discoveries in the geologic history of plants and animals convince us more and more of the long duration of the unrecorded stage of evolution.

COMMUNICATION

To the Editor:

The comparison of shapes of valleys to capital letters of the alphabet —U for glaciated valleys and V for those due to ordinary river erosion has long been used quite helpfully in textbooks of physiography. I have found a few other letters of the alphabet helpful in the same connection. I submit them to you and to other teachers for suggestion and criticism:

I-shaped valleys—extremely young, of the cañon type, corrasion very rapid with relation to lateral weathering;

V-shaped valleys due to river erosion, width of V dependent on the ratio of weathering to corrosion;

Y-shaped valleys—rejuvenated, the grade of the river has been recently increased by uplift or uptilting of the head waters;

W-shaped valleys—the river acting as a distributary in a flood plain which is highest near the river, grade of the river therefor decreasing either by uptilting of the mouth or down tilting of the head waters, or otherwise. The application of the letter W to this form of valley is something of a stretch, yet I find it well worth while to emphasize the fact that such streams as the Mississippi and the Poe have as the highest part of the flood plain that immediately near the river, so that a cross-section of their valleys has more the shape of a cross-section of a plate or pan. In fact I have used the term pan-shaped for these sections. But it is schematically desirable to use another letter, and W lends itself fairly well. U-shaped valleys remain as usual glaciated valleys.

ALFRED C. LANE

REVIEWS

The Foundry Sands of Minnesota. By G. N. KNAPP. *Bull. 18,* Minn. Geol. Survey, 1923, pp. 105. figs. 13, tables 17.

Foundry sand has been defined heretofore as a sand or loam which has the following properties: it must contain sufficient clay or other binding material to enable it to stand up in the mold; it must be sufficiently porous to allow steam and gases to escape, and must be sufficiently refractory to resist fusion. But precise measurement of any of these properties has rarely been attempted, and figures expressing these properties quantitatively are very meager, or wanting.

The purpose of the investigations described in this Bulletin was to place these properties on a quantitative basis. A careful measurement of each of the essential properties of molding sands was undertaken, and the absolute and relative values of the results are given in definite figures and percentages.

The clay content of various types of foundry sands was accurately determined by elutriation, and is given in percentages by weight. The bonding power of the elutriated clay was found to vary with the kind of clay, and this difference in bonding power was attributed to the probable variation in the amount of colloidal material present in clays of different types. The colloidal content was not determined.

The moisture content of sands in actual foundry practice was found to vary from 1.7 per cent to 12 per cent by weight, this variation being due to proportioning of the fine and coarser sizes in the sand, the clay content, and the kind of clay. The amount of colloidal material was probably also an important factor.

The mechanical analyses of the sands and loams were carried to a greater degree of refinement than heretofore. The laboratory work demonstrates that sizing of sands by screen sieves cannot be done accurately with the clay and silts present, because of the inevitable presence of clusters of fine grains, and the adhering of fine grains to the coarse ones. The silts are shown to play an important rôle in granulation, on which permeability in molded sands largely depends.

The permeability of the sands in the natural condition, as well as in the molded state, was determined by actual measurement which had

not previously been done. The permeability tests demonstrate that sand when moistened and rammed into a mold is usually from two to ten times as permeable as the same sand in a dry, disintegrated state, which shows the extent to which granulation is effective. The permeability tests serve also to emphasize what was inferred in advance, that the porosity of a sand in its natural state is no measure of, and not necessarily an index to the permeability, either in the natural state or after being molded. The permeability of the molded sand is a function of the structure developed, which in turn is largely a matter of granulation.

When the field work was done for this Bulletin in 1918, foundry sands and clays were being shipped in large quantities from distant localities in New York, Missouri, Illinois, Ohio, Kentucky, and Colorado. As a result of this investigation nearly all of the materials that were required in the foundries were found to occur in Minnesota.

Contributions to the Paleobotany of Peru, Bolivia and Chile. Five papers by EDWARD W. BERRY. "The Johns Hopkins University Studies in Geology," No. 4. Baltimore, 1922. Pp. 221, pls. 25, figs. 9.

The following five topics are treated in these papers: "Carboniferous Plants from Peru"; "The Mesozoic Flora of Peru"; "The Flora of the Concepcion-Arauco Coal Measures of Chile"; "Pliocene Fossil Plants from Eastern Bolivia"; "Late Tertiary Plants from Jancocata, Bolivia."

In his first paper, Berry examines the coal-bearing rocks south of the Port of Pisco on the peninsula of Paracas, which is about 220 km. south of Callao. He thinks that these deposits correspond to the Westphalian stage. His conclusions are based largely upon the fossil plants found in these deposits. The following genera are represented by rather common species: Palmatopteris, Eremopteris, Calamites, Calamostachys, Lepidodendron, Lepidophyllum, Lepidostrobus, Stigmaria, and Knorria.

Berry's second paper in this collection attempts to sum up our present knowledge of the Peruvian Mesozoic flora. Mesozoic rocks are very widespread in Peru, and are particularly prominent in the Cordillera Occidental, especially between latitudes 5° and 13° S. Most of the Jurassic and Cretaceous horizons are represented. A collection of fossil plants was made on the San Lorenzo Island. Berry gives a list of genera from the Mesozoic of Peru, all of which, with one excep-

tion, are represented in the English Wealden, and only one is found in the Potomac flora of Eastern United States.

The third paper deals with the Miocene flora in southern Chile, and with deposits which are of particular interest, because they represent the Tertiary coal fields of Chile. The genus Araucaria is very prominent in this flora, and Berry discusses at considerable length the Mesozoic and Tertiary distribution of Araucarias throughout the world, with reference also to the recent occurrence of this type. The floral elements of the Tertiary in Chile are compared with other fossil floras and present-day distribution of plants in South America.

The next paper deals with the Pliocene fossil plants from eastern Bolivia. The flora and its environmental conditions are discussed. Berry draws some conclusions as to the changes of level, in consequence of the uplift of the Andes Mountains, which has taken place since this flora existed. His conclusion is that the rise must have been not less than 6,500 nor more than 9,000 feet. The author includes a list of these plants which he calls the Pisllypampa flora.

The last paper deals with the late Tertiary plants from Jancocata, Bolivia. This flora, according to his determination, is of Plio-Pleistocene age.

The foregoing articles contain much valuable information on the climatological and ecological conditions under which these floras grew up. They are a valuable addition to our knowledge of South American fossil plants. But there is still a great deal to be done along these lines, although the departments of mines of the South American states seem to have been not unmindful of the interesting plant deposits in their respective countries.

A. C. N.

Rocks and Their Origins: By GRENVILLE A. J. COLE. Cambridge University Press, 1922. Pp. 175, figs. 20.

This little book, the first edition of which came out in 1912, is inscribed by the author as "intended for those who are not specialists in geology." A comparatively slight knowledge of geologic technology is presupposed on the part of the reader; and the style of the book is simple and clear, but the simple treatment does not entail any loss of accuracy of statement.

A brief introductory chapter brings out the distinction between rocks and minerals, and lists the more common minerals with their chemical compositions. A chapter each on limestones, clay rocks, sandstones, igneous rocks, and metamorphic rocks constitutes the remainder of the

volume. Each rock type is treated rather fully as to origin, varieties, alteration, and surface expression. The current conceptions of the different rock-forming processes are developed historically, the most important contributory theories, past and present, being discussed in each case. It might be said that this is done too fully for an elementary book; but, on the other hand, the critical background which this presentation gives the reader is valuable, and will make the book of interest to many geologists.

The extensive illustrations used to bring out different points are interesting and effective, and are chiefly drawn from Europe and other parts of the Eastern Hemisphere, thus being fresh to many Americans.

T. B. R.

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Summary of the Geology of the Beartooth Mountains, Montana. By ARTHUR BEVAN.

Was there Pennsylvanian-Permian Glaciation in the Arbuckle and Wichita Mountains of Oklahoma? By SAMUEL WEIDMAN.

The Paleozoic Rocks Found in Deep Wells in Wisconsin and Northern Illinois. By F. T. THWAITES.

The Structural Geology of British Malaya. By J. B. SCRIVENOR.

The Ferruginous Chert Formations of Notre Dame Bay, Newfoundland. By EDWARD SAMPSON.

Almandite and its Significance in the Contact Zones of the Grenville Limestone. By GEORGE W. BAIN.

VOLUME XXXI NUMBER 5

THE

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THE MINERALOGRAPHY OF THE FELDSPARS PART II—(*Concluded*)

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THE SODA-LIME SERIES

The problem of the isomorphism of the plagioclase feldspars has not been fully understood. That they are a series of solid solutions is a matter upon which there is little disagreement, but how can albite and anorthite be isomorphous? On this question Wherry[1] has reached the conclusion that it is a case of atomic isomorphism, with one aluminum atom occupying a sort of nuclear position in both end-members; the second aluminum atom of anorthite being definitely a replacement of one silicon atom of albite. This is indicated by the formulas: $NaAl(Si_3O_8)$ and $CaAl(AlSi_2O_8)$.[2]

[1] E. T. Wherry, "The Plagioclase Feldspars as a Case of Atomic Isomorphism," *Amer. Min.*, Vol. VII, No. 7 (July, 1922), 113–21.

[2] The Asches in *The Silicates in Chemistry and Commerce*, p. 295, say: "Tschermak assumed that the [plagioclase] feldspars were isomorphous mixtures of two silicates—albite and anorthite—to which he gave the following formulas: Albite $NaAlSiSi_2O_8$; Anorthite $CaAlAlSi_2O_8$." If this is correct, the idea expressed by Wherry is not a new one at all and the credit should be given to Tschermak. See E. T. Wherry, "Volume Isomorphism in the Silicates." *Amer. Min.*, Vol. VIII (1923), pp. 2–3. F. Zambonini (H. S. Washington), "The Isomorphism of Albite and Anorthite," *Amer. Min.*, Vol. VIII (1923), pp. 81–85. T. Sterry Hunt, *Amer. Jour. Sci.*, Vol. XVIII (1854), p. 270; *Phil. Mag.*, Vol. IX (1855), p. 354.

It is a little difficult to understand why the majority of American mineralogists seem to favor the view that the two silicate radicals (Si_3O_8) and (SiO_4) are mutually equivalent. It was an oversight, however, for Wherry to include the writer in this group.

The writer believes that Wherry has reached a very reasonable explanation of the isomorphism of the series.

THE POTASH-LIME SERIES

This system, called the "oranite" series in Part I, is the one that is rarely recognized. Several illustrations, however, from the Adirondacks were there recorded. Such feldspars are intergrowths and mechanical aggregates, not homogeneous single-phase solid solutions.[1]

Wherry[2] in the July and October numbers of the *American Mineralogist* took exception to some of the statements in Part I. These criticisms, based upon misunderstandings, have been reconsidered and corrections have been made in the December number.[3] We are essentially in agreement.

Oranite is not a hypothetical intergrowth. A dozen slides in the writer's collection contain examples. Furthermore various investigators, including Dittler[4] and the writer, have succeeded in synthesizing them in the laboratory. They correspond to *perthite.*

The reason for giving this system a name is as follows: The Adirondack occurrences consist of labradorite ($Mi_5Ab_{45}An_{50}$) with blebs of potash feldspar ($Or_{85}Ab_5An_{10}$) imbedded in it. This intergrowth is approaching, as a limit, the potash-lime binary system; hence a name is very desirable and quite analogous to perthite.

The results of thermal studies on artificial feldspars by the investigators above mentioned show that on adding orthoclase to bytownite or to anorthite zonal grown crystals can be made up to 10–15 per

[1] See page 236 of Part I. See Harker, *op. cit.*, p. 246; William S. Bayley, *Descriptive Mineralogy*, 1917, p. 408.

[2] E. T. Wherry, *Amer. Min.*, Vol. VII, No. 7 (July, 1922), p. 115. Also Wherry misquotes the writer in *Rev. Geol.*, January, 1923, p. 30, No. 22.

[3] E. T. Wherry, *Amer. Min.*, Vol. VII, No. 12 (December, 1922), p. 212.

[4] Emil Dittler, "Über die Darstellung kalihaltiger basischer Plagioklase," *Min. und Petro.*, Neue Folge., XXIX (1910), 273–333; "Über das Verhalten des Orthoklase zu Andesin und Celsian über seine Stabilität in künstlichen Schmelzen," *Min. Petr. Mitt.*, XXX (1911), 118–27.

cent of orthoclase but beyond that amount the cooled material consists of two phases. The maximum separation of the potash-rich and the lime-rich feldspars occurs at about 45 per cent Or, 55 per cent An. It is not the intention of the writer to convey the idea that the results of these thermal studies prove that this percentage fixes the position of the eutectic point, but only that it is probably in this neighborhood. An artificial mixture of 40 per cent orthoclase, 20 per cent albite, 40 per cent anorthite, when held at 1250° C. for several hours and then cooled rapidly showed a pseudohomogeneous solid solution, a crypto-oranite (to parallel Brögger's "cryptoperthite"). This sample when "annealed" at a lower temperature for a longer time became a micro-oranite, consisting of two phases. This separation became more perfect as the time of annealing was extended. Similar treatment of anorthoclase gave no such results. The interpretation of these observations is that the viscosity of the lime-free feldspars prevents extensive separation of the two phases. But with increased lime the viscosity of the melt is proportionally lower, allowing a greater separation.[1]

The petrogenetic significance of this is that magmas which contain potential oranitic feldspar give rise to two-phase systems consisting of orthoclase-rich and plagioclase-rich feldspar. This applies to many granites, syenites and monzonites. The presence of such potential oranitic feldspars in the common rocks is often concealed by recasting the chemical analysis into the *norm*, and while it is not so easy to secure the *mode* of an igneous rock, the latter alone shows the real distribution of the feldspar components into their respective phases. Such a procedure is necessary to obtain a true conception of the nature of the feldspars in many rocks.

The reader may observe that the writer is extending the meaning of the term "oranite" to cover molten feldspar mixtures. We are so much in the habit of considering our minerals as solid substances (the usual definition) that we lose sight of the manner of their crystallization. To give to these feldspathic melts a definite name emphasizes their existence, and leads us to be on the lookout for the end-products of such processes.

[1] A. L. Day and E. T. Allen, "The Isomorphism and Thermal Properties of the [Plagioclase] Feldspars," *Carnegie Inst. Pub. 31* (1905).

THE ZONING OF FELDSPARS

It was Hoepfner[1] who first called attention to zonal structures in plagioclase. Rosenbusch[2] early explained it as due to periodic interruptions during crystallization and to selective decomposition. Michel-Levy[3] considered zonals as "the result of a submicroscopic twin lamination after the albite and pericline laws." Later Rosenbusch showed that in many cases the kernel of a zonal is more basic than that of the shells. He explained this on the basis that there exists an isomorphous lamination in which an original, basic, central crystal is surrounded by shells of other plagioclase which gradually become more and more acid. The great majority of zonals can be fully understood by following the crystallization of a melt by means of a thermal diagram. The phenomenon is not confined to feldspars nor to isomorphous minerals; it is also found in many alloys.[4]

In deep-seated rocks zonals are not common, nor do they occur in glassy rocks. Yet in certain porphyritic rocks zonal feldspars are frequently found. This simple observation has an important genetic significance. In Part I, page 215, the statement is made that the degree of homogeneity is a function of the rate of chill. Bowen[5] says: "There is a certain definite rate of cooling which gives maximal zoning. . . . . With a somewhat quicker rate of cooling, the range of zoning is not so great owing to a moderate degree of undercooling, and when the undercooling is very great there is no zoning at all." This relation is graphically expressed by Figure 7 which, of course, is to be interpreted qualitatively and not quantitatively. We can make use of this observation in arriving at the conditions under which rocks of this kind solidified.

[1] C. Hoepfner, "Über das Gestein des Mte. Tajumbia in Peru," *N. Jahrb. f. min. u. geol.*, II (1881), 164–92; J. Blumrich, *Tscher. Min. u. Petro. Mitt.*, XIII (1892), 239, 258; A. Pelikan, *ibid.*, XVI (1896), 1.

[2] Rosenbusch-Iddings, *Microscopical Physiography of the Rock Making Minerals*, pp. 307, 326.

[3] A. Michel-Levy, *Comp. Rendu*, XCIV (1882), 93, 178.

[4] Edgar Bain, "Cored Crystals and Metallic Compounds," *Chem. and Met. Eng.*, Vol. XXVIII, No. 2 (January 10, 1923), 65–69; Walter Rosenhain, *ibid.*, No. 10 (March 7, 1923), 442–46; *Trans. Amer. Inst. Min. and Met. Eng.*, June, 1923.

[5] N. L. Bowen, *Jour. Geol. Suppl.*, XXIII (No. 8, 1915), 33.

Zonal feldspars are not exclusively plagioclase, for orthoclase, microcline, and anorthoclase occur with this structure. "In certain porphyritic granites (Rapakiwi) oligoclase forms a shell about phenocrysts of orthoclase."[1]

THE TWINNING OF FELDSPAR

It seems a pity that while the twinning phenomena of feldspars are listed and illustrated in every textbook of any pretensions, no adequate theory is offered in explanation. Harker,[2] following Vogt,[3] has stated that microcline structure seems "to be sufficiently accounted for by spontaneous changes consequent upon fall of temperature," a view maintained in Part I. Still the setting up of microclinic structure is also a function of stress.[4] The two ideas can be united by saying that the inversion of orthoclase to microcline (if we grant dimorphism) involves a change in volume[5] and this introduces stress into the system. Now it is conceivable that inversion may take place and a change in volume ensue, but at such a slow rate that twinning does not occur. The writer has repeatedly observed in cutting and grinding feldspars for thin sections that microcline twinning is produced by the process. Hence he reasoned that gentle and slow grinding might result in a section free from twinning. This proved to be correct after repeated failures. The microcline from Lincoln County, Nevada, thin sectioned in this careful manner, showed the following extinction angles, (010) 5.6°, and (001) 16.1° *although exhibiting no microcline twinning*, even when magnified to 2,400 diameters. An ordinary slide of the same specimen showed "scotch plaid" structure and the same extinction angles. Iddings[6] says "Microcline . . . . may be free from lamellar twinning and resemble orthoclase except in its optical orientation." The conclusion is clear: that microcline twinning is not always characteristic of microcline but merely of a strained condition

[1] J. P. Iddings, *Igneous Rocks*, II, 47.

[2] *Op. cit.*, p. 260.

[3] Vogt, *Tsch. Min. Petr. Mitt.* (2), XXIV, 537–41.

[4] See Part I, pp. 275–76.

[5] Note the two sets of specific gravities for potash-soda feldspars.

[6] *Op. cit.*, p. 46.

perhaps due to volume change on inversion. Or it may be that microcline and plagioclase twinning are often produced by stress in making thin sections. Incipient twinning may always be present in plagioclase or microcline as a result of atomic arrangement. If it is very minute it may be exaggerated by stress to a point where it can be seen.

> Many years ago . . . . George W. Hawes[1] noticed in slides of . . . . [anorthosite] some feldspars which failed to afford the twinning striations, yet which he suspected of being plagioclase. Analytical tests demonstrated that they were. The same untwinned character may reappear so that the observer must be on his guard, but it is also true that a chance section parallel to the twinning plane would be without striations.[2]

In some cases ordinary slides of normal andesine, labradorite and especially bytownite show no twinning at all. The feldspars are clear and so similar to orthoclase under the microscope that unless extinction angles or, better still, the indices of refraction are determined it may well pass for that mineral. This development of twinning by pressure is more noticeable in albite ranges and decreases in intensity as the lime range is approached. The bytownite from Crystal Bay, Minnesota[3] ($Mi_{2.0}Ab_{24.7}An_{73.3}$) when thin-sectioned with great care is entirely free from twinning, while an ordinary slide prepared by Tomlinson exhibited broad albite twinning. Thus the writer would voice a word of caution: All feldspars may occur in thin section absolutely untwinned and hence the presence or absence of twinning is not a reliable means of identification.

POTASH-SODA-LIME FELDSPARS

In Part I the writer maintained that all natural feldspars are systems of three components and should, when elaboration demands, be recorded as such (cf. the composition of the feldspars here discussed). Professor A. N. Winchell has kindly called my attention to the fact that Sabot[4] reached that conclusion in 1915. Sabot says (in an abstract in translation):

[1] George W. Hawes, "On the Determination of Feldspars in Thin Sections of Rocks," *U.S. Nat. Mus. Proc. 1882*, IV, 134–36.

[2] J. F. Kemp, *New York State Mus. Bull. 138* (1910), 30.

[3] Specimen 969B.

[4] R. Sabot, *Compte Rendu des Séances de la Société de Physique et de l'Histoire Naturelle de Génève,* XXXV (1918), 72; XXXVII (1919), 51.

Using the data and the graphic methods of Professors Nitikin and Koloulsky . . . . , in spite of the fine precision in their work, the points of the curves of the representative feldspars were not exactly upon the published curves of either Michel-Levy[1] or those of Nikitin. The deviation is to be explained by the presence, in the plagioclase series, of the term $KAlSi_3O_8$, triclinic, frequently entering [into the composition] in notable quantities. The published data of the feldspars, for example that of the extinction [angles] for a determined face, should not be distributed upon a curve, but be spread more or less over an area, according to the proportion of the potash [component] present.

Fedorow[2] said that "Another question which the law of Tschermak is not competent to explain[3] is the presence of potassium often in notable proportions in the majority of plagioclases."[4]

J. Schetelig,[5] in speaking of the discrepancy between the optical and chemical determination of the composition of an albite says:

The difference is due either to small errors in the exact orientation of the sections and in the determination of the angles of extinction, or *to the hitherto not exactly known influence of the relatively large amount of the Or-component on the optical properties of the plagioclases.* [The writer's italics.] The tables of F. Becke for computation of the composition of the plagioclase are based upon careful investigation of pure mixtures of the Ab- and An-components, but the influence of the Or-component is not taken into consideration.

If there should be a series of thermal diagrams instead of a single binary one to show the crystallization of the potash-soda series so that all potash-soda feldspars, no matter of what origin, could be fully understood, then there should be a group of three dimensional models to show all possible feldspars consisting of three components. While the phenomenon of undercooling is especially noticeable in the case of the potash-soda series, we should not forget that the other

[1] E. S. Larsen, in a review of Johannsen's recent *Essentials for the Microscopical Determination of Rock-forming Minerals* (*Eng. and Min. Journal-Press*, Vol. 114, No. 18 [October 28, 1922], p. 775), says: "It is regrettable . . . . that for the Michel-Levy method the old diagram has been used. Determinations made by this diagram are commonly in error as much or even greater than 10 per cent, whereas by using the diagram published by Wright the determinations check with those made by other methods."

[2] E. von Fedoroff (Fedorov, Fedorow), "Universalmethode und Feldspathstudien," *Zeitschr. f. Kryst. Min.*, XXIX, 604.

[3] This criticism is too severe. Tschermak would consider the potash feldspar to be *partially* isomorphous with soda and lime components.

[4] As cited by Elvira Carrasco, "Contribution à l'étude des macles de feldspaths au moyen de la méthode de Fedoroff," *Bull. Soc. Vaud. Sc. Nat.*, LII, 483–564.

[5] Adolf Hoel and J. Schetelig, *Nephelin-Bearing Pegmatitic Dykes in Seiland*, 1916.

feldspars outside of the anorthoclase-cryptoperthite ranges exhibit the same phenomenon, although to a lesser degree. As has been

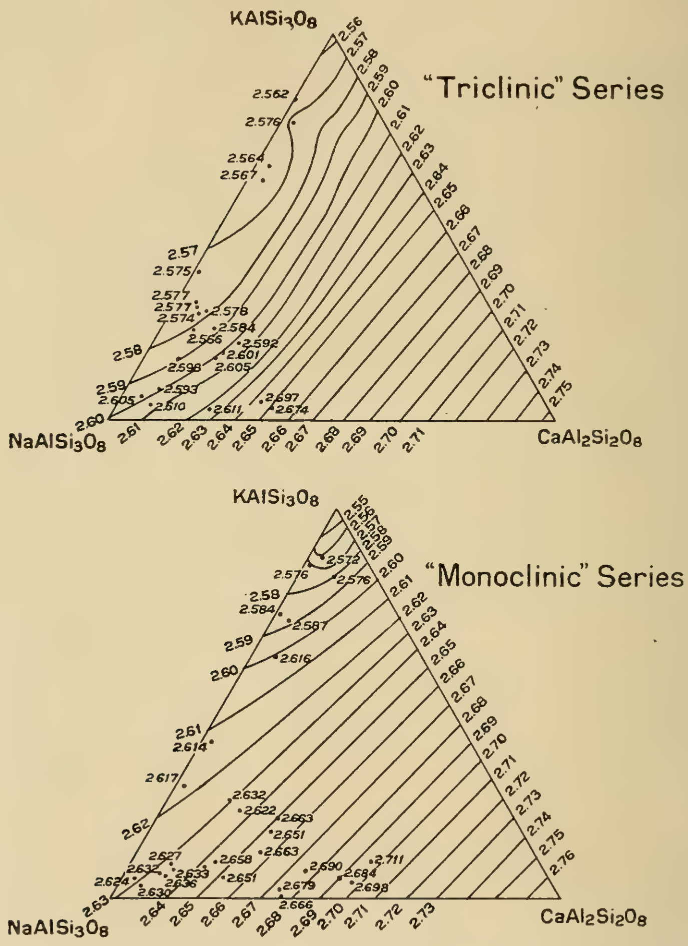

FIG. 4.—Plot of specific gravities of the potash-soda-lime feldspars shown by iso-gravity lines. Upper figure: Microcline, albite, anorthite, "triclinic" series. Lower figure: Orthoclase, "barbierite" and "barbierite"-rich anorthite, "monoclinic" series. Offered with full knowledge that they leave much to be desired.

already stated, the degree to which they undercool is dependent upon their origin; consequently it follows that the position of the solubility lines (perhaps best appreciated when projected to the

triangular base) is controlled by the conditions prevailing during crystallization. These lines are farther away from the sides of the diagram when excessive undercooling obtains, in fact they may come together near the center as in certain anorthoclases, producing a

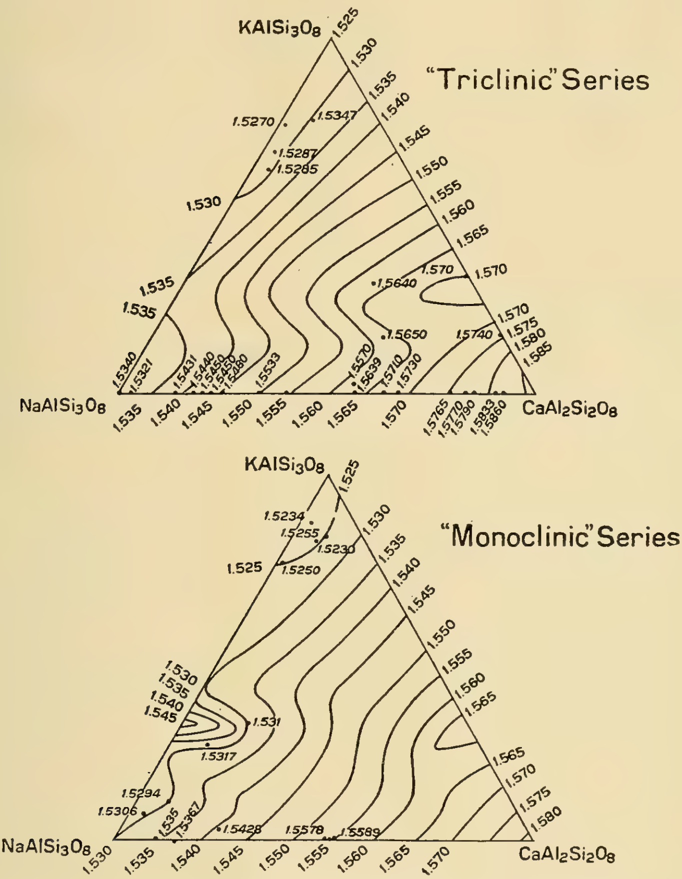

FIG. 5.—Plot of β values of indices of refraction of the potash-soda-lime feldspars. These diagrams are to be regarded as tentative and subject to revision.

series of solid solutions with a minimum, or may be close to the sides when equilibrium and exsolution are unhampered. Rapidly cooled albites, andesines, and oligoclases may thus contain a higher percentage of the potash component than the more slowly cooled equivalents. As the viscosity of such melts decreases with increased

lime it is evident that the solubility lines of the more basic plagioclases maintain a more constant position irrespective of the rate at which they have been cooled than do those of the alkali-rich feldspars. Thus we can expect to encounter such feldspars as potash-oligoclase more frequently than potash-bytownite.

It becomes necessary, therefore, to project all plotted data, specific gravities, extinction angles, indices of refraction, optical angles, crystallographic angles, etc., upon a triangular base and employ contours. Figures 4, 5, and 6 represent a revision and extension of the work suggested in Part I.

SPECIFIC GRAVITIES

The diagrams of the specific gravities of feldspars given in Part I (Figs. 12-6 and 12-7, p. 250) were only tentative, hence the effort is now made to improve their quality as it is believed thay may be of value to petrographers and mineralogists. The writer tabulated all of the available analyses of feldspars of which the specific gravities were given. These analyses were then recast into three components. This information is to be taken with caution in that many of the chemical analyses are undoubtedly inferior to those demanded today. Although the writer wishes he possessed the skill, the facilities and the time to secure afresh this needed information, he was forced to make use of these rather uncertain data.

From these data a "peg model" was constructed which clearly showed two sets of pins, one for the "monoclinic" and the other for the "triclinic series." The results of this study are given in Figure 4.

INDICES OF REFRACTION

A similar "peg model" was constructed from analogous data giving the beta values of the index of refraction of the potash-soda lime feldspars. Here the data is less comprehensive and the difficulties of the interpretation are consequently greater. At first it was thought that it was not possible to recognize two sets of pins, representing the two series, and as a result the contoured surface of the plaster model made from the peg model was most irregular. Experience with the specific gravity peg model led the writer to attempt to classify the pins into two sets, each representing a sur-

face. Whether there are two distinct sets or not is a question still to be investigated. However, their classification into two groups, depending upon their height, did result in two contoured surfaces which are reasonably regular. These diagrams are offered with the full appreciation that they leave much to be desired. Slight modifications of some of the values were necessary in order to make them "fit." The majority of the analyses of plagioclase lacked the determination of K_2O. In these cases the writer assumed the per cent of the potash component to be from 2 to 4 per cent. Larsen[1] has measured the indices of the plagioclase series and recorded the results as $\frac{\alpha+\beta+\gamma}{3}$. This curve has been modified so as to agree more closely with the curves of Rosenbusch-Wülfing,[2] Wright,[3] and Tsuboi.[4] It was also found that Dittler's[5] gamma values of synthetic oranitic feldspars, when lowered to the probable beta values were too low and they were arbitrarily raised by adding from .003 to .005 to them. In a similar way it was found that Wright's[6] *molecular* percentage curve when translated into the more usable *weight* percentage form was lower than those for most natural feldspars. Even the curves of Iddings[7] and of the Winchells[8] seem to give more consistent results on natural specimens, though there is every reason to believe that Wright's data on synthetic material is more accurate. The real point is that the average petrographer deals with natural and not with artificial minerals. The cause of these discrepancies may be explained by the lack of "impurities" such as magnesia and iron in the synthetic material. It is to be regretted that because of the paucity of accurate determinations of the physical constants of synthetic minerals we are compelled to

[1] E. S. Larsen, *Amer. Jour. Sci.*, XXVIII (1909).

[2] As given by Albert Johannsen, *Essentials for the Microscopical Determination of Rock-Forming Minerals and Rocks*, 1922.

[3] Fred E. Wright, *Am. Jour. Sci.* (4), XXXVI (November, 1913).

[4] Given by Albert Johannsen. Tsuboi, *Jour. Geol. Soc. Tokyo*, XXVII (1920), in Japanese.

[5] E. Dittler, *Tsch. Min. Petro. Mitt.*, XXIX, 39 and 387.

[6] Fred E. Wright, *Amer. Jour. Sci.* (4), XXXVI (November, 1913), 540.

[7] J. P. Iddings, *Rock Minerals.*

[8] N. H. and A. N. Winchell, *Elements of Optical Mineralogy*, 1909, p. 200.

modify such results in order to make them commensurate with the values of natural minerals.

To supplement the available data secured from the literature on the subject, the writer has measured the indices of refraction of a number of critical feldspars, by a development of the refractive index liquid immersion method.[1]

We find a serious difficulty in that some feldspars are mixtures of two different series. Foerstner has pointed out that such feldspars actually occur. When this is the case the indices are intermediate in value. The beta values of such feldspars when their indices are plotted will not lie on a surface but in a zone or a "stratum" of values. If a sufficient number of pegs has been available then the maximum and minimum values would give the two surfaces—one for "monoclinic" and the other for "triclinic" feldspars. Until

[1] The index of such oils is lowered in value with a rise in temperature while that of the feldspars rises as they are heated.

See C. H. Wright, *Jour. Ind. Eng. Chem.*, 1919:

$$n=(n_1-1)\frac{(1-Kt)}{(1-Kt_1)}+1$$

Where n and n_1 are the indices at the temperature t and t_1, and K=modulus of dilatation, which for fixed oils generally = .00076.

The rate of decrease in value of the oils, however, is far greater than the increase in the index of the crystals when raised from room temperature to 70° C. The increase is so slight that it may be ignored, as it involves an error of only one figure in the fourth decimal place at 70° while most of the oils in the writer's collection have a coefficient ranging from .000306 to .000609 per 1°, the average being between .0004 and .0005. The indices of these oils have been measured on a Spencer (Abbé) refractometer at various temperatures from 10° to 70° C. The results were recorded in the form of curves, which are periodically rechecked to insure accuracy. The instrument is accurate to .0003, although it is said to be .0002 (H. S. Simms, *Jour. Ind. and Eng. Chem.*, June, 1921). The fragments (passed through 100-mesh and caught on 120-mesh screens, approximately .3 mm. in diameter) are mounted in an oil whose index at normal room temperatures is higher than any of the indices of the feldspar. The slide is then placed in an electric hot stage (a remodeled biological stage, with an adjustable thermostat) and the temperature raised slowly until the Becké test, using monochromatic light, shows that the crystal and oil have the same index. The temperature of the stage is noted (a Taylor Instrument Company's thermometer standardized against the thermometer of the Spencer Refractometer) and the corresponding value in index read from the curve for that particular oil. Furthermore these results have been checked by using Merwin's dispersion diagram (E. Posnjak and H. E. Merwin, *Jour. Amer. Chem. Soc.*, September, 1922). In this manner the indices of both phases of a perthitic feldspar may be conveniently measured from a single mount.

these are forthcoming the writer cannot offer diagrams which are as accurate as desired.

Kozu and Suzuki[1] report that the indices of a moonstone from Korea ($Or_{61.9}$ $Ab_{32.7}$ $An_{5.4}$) vary among the several specimens at hand and even from place to place within the same crystal. To find zonals in orthoclasic feldspars is to be expected but here the indices may vary as much as .002 between two crystals from the same locality. This indicates some of the difficulties in the way of a satisfactory index of refraction diagram for the potash-soda-lime feldspars.

EXTINCTION ANGLES

Similar remarks apply to values of extinction angles. Here again a peg model undoubtedly suggests two series. The plotting of the data is given in Figure 6.

In Part I (p. 229) it was stated that "as the amount of the sodium component [in orthoclase] increases . . . . the (001) extinction angle changes from zero to about three degrees." These potash-soda feldspars were called monoclinic. Professor A. N. Winchell[2] has called the attention of the writer to this obvious error. The extinction angles of strictly monoclinic minerals measured on the trace of the (010) face in cleavage fragments or sections parallel to (001) must necessarily be zero. However, it may be said that the writer employed the term "monoclinic" as a general distinctive name for the orthoclase-barbierite series as contrasted with the triclinic microcline-albite series. It was thought unwise to introduce a new term. As a matter of fact, the statement that the angle varies from zero to three degrees may mean that the specimens so plotted were mixtures of the two series and hence the term triclinic should be applied instead. If the (001) extinctions remain zero it may be that it is because this specimen is a representative of pure orthoclase-barbierite feldspar. Thus the microscopic determination of the potash-soda series is complicated by (1) the effect on the physical properties by the presence of the lime component, (2) by the presence of nephelite-carnegieite, (3) by the possible dimorphism

[1] S. Kozu and M. Suzuki, "Optical, Chemical and Thermal Properties of Moonstone from Korea," *Sci. Repts. of Tohuko Univ.*, Ser. III, Vol. I (No. 1, 1921), p. 20.

[2] Personal communication, May 28, 1921.

of both end members (minals) and (4) by the probable mixture of these two series.

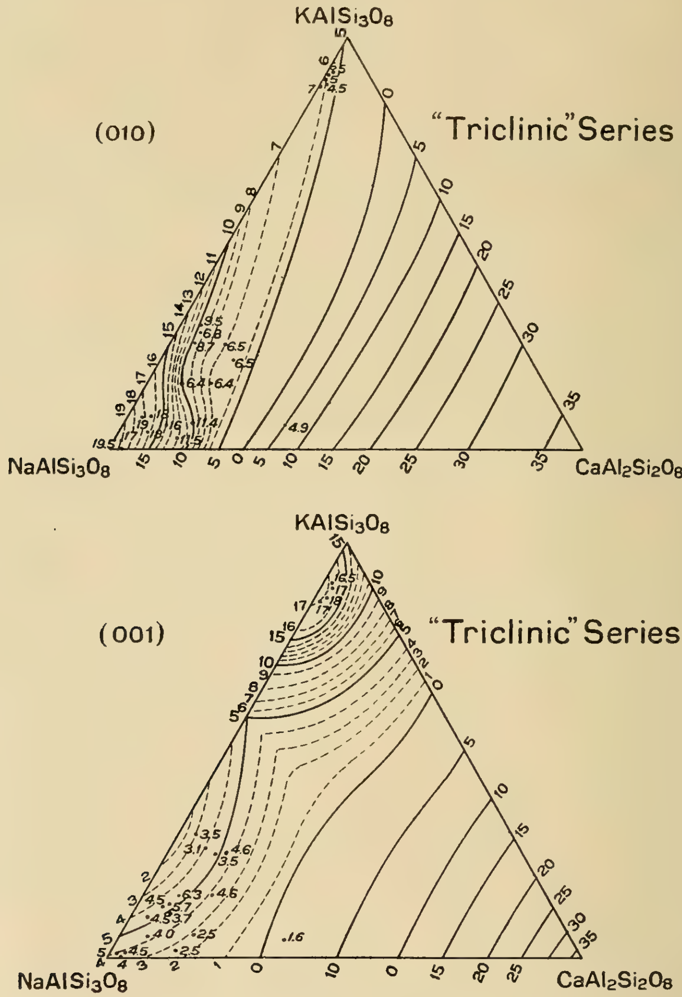

FIG. 6.—Plot of extinction angles for potash-soda-lime feldspars. Upper figure: (010) face. Lower figure: (001), base. Both for "Triclinic" series. The monoclinic series not attempted, tentative, subject to revision.

The writer wishes to correct an error in Part I. On page 251 the statement is made that in using the conventional curves for extinction angles of the soda-lime series "it is not possible to deter-

mine the percentage of the lime and potash members with anywhere the same accuracy" as the soda member. "The most satisfactory means . . . . is to consider that the value of the extinction angles gives the percentage of the *soda* component only." From this and the average amount of potash feldspar usually found in plagioclase

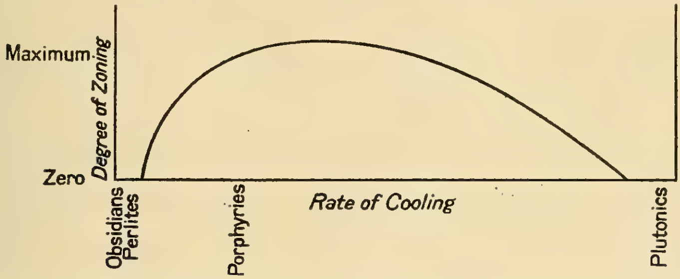

FIG. 7.—Diagram suggesting that porphyritic feldspars are able to possess the maximum amount of zonal structure while feldspars in obsidians, perlites, and plutonics exhibit little or no zonal habit. This diagram is to be considered in a qualitative and not in a quantitative manner.

the other two components can approximately be ascertained. The word "soda" (in italics) is in error. The truth is that extinction angles give the *lime* component more accurately and by assuming 4 to 6 per cent potash feldspar, the amount of the soda component is found by subtracting the sum of these from one hundred.

SUNSTONE AND AVENTURINE FELDSPARS

Viola[1] and Andersen[2] have investigated the aventurine feldspars and the latter reached the conclusion that the included plates of definitely oriented hematite (or magnetite, ilmenite, rutile, etc.) are due to exsolution.[3] This suggests that the original melt could hold a compound of iron in solution while molten but the decrease in solubility of the feldspar for the iron compound with falling temperature caused its separation. Furthermore potassium feldspars are often pink while albite is more frequently white.[4] This may mean

[1] C. Viola, *Zeitschr. f. Kryst.*, XXXIV (1901), 171.

[2] Olaf Andersen, *Amer. Jour. Sci.* (4), XXXIX (1915), 379.

[3] See Alfred Harker, *op. cit.*, p. 257; Judd, *Quar. Jour. Geol. Soc.*, XLI (1885), 374–89; J. H. L. Vogt, *ibid.*, LXV (1909).

[4] "Flesh-colored albite occurs as well as flesh-colored orthoclase."—Iddings, *Igneous Rocks*, Vol. II, p. 46.

that potash feldspar melts can absorb or have a selective ability to dissolve iron-bearing minerals. Such a theory would explain the colorization of orthoclase and microcline in granites, syenites, etc. In contrast to this idea is the light that is cast when the ferric feldspars are considered. As long as feldspars are considered as salts of

TABLE V

ORTHOCLASE, MADAGASCAR

	1	2	3a	3b
SiO_2	64.19	63.99	64.76	64.72
Al_2O_3	16.62	18.02	17.98	17.97
Fe_2O_3	2.88	0.97	1.18	1.20
FeO	0.18	0.00	0.09	0.09
MgO	....	....	0.08	0.09
CaO	....	0.50	0.16	0.10
BaO	n.d.	0.06	n.d.	n.d.
Na_2O	0.34	1.86	1.07	0.94
K_2O	15.81	14.32	15.39	15.18
H_2O	....	0.51	.20	0.19
Total	100.02	100.23	100.91	100.48
$KFeSi_3O_8$	11.02	5.05	4.54	4.61
$KAlSi_3O_8$	82.50	81.37	86.63	85.45
$NaAlSi_3O_8$	2.89	10.74	9.06	7.96
$CaAl_2Si_2O_8$	....	2.48	0.79	.49
$BaAl_2Si_2O_8$	....	0.15	....	....
Total	96.41	100.76	101.02	98.51
Excess SiO_2	1.92	....	....	....
Excess Al_2O_3	1.32	....	....	....
	99.65	....	....	....

1. Lacroix, *Min. de la France*, XXIX (1913). Boiteau, analyst. Deep lemon yellow. (Kindness of Henry S. Washington.)

2. Lacroix, *Min. de Madagascar*, I (1922), 560. Raoult, analyst. Nearly colorless. (Kindness of Henry S. Washington.)

3. Material from Ward's Natural Science Establishment. Madagascar Mining Co. Analysis by H. B. Croasdale, Fraser Laboratories, New York City.

ortho- and trisilicic acids the non-replaceability of the aluminum by ferric iron is indeed striking. The apparent absence of such feldspars is more understandable if these minerals are alumino-silicates. However, $KFeSi_3O_8$ has been synthesized by Hautefeuille and Perrey[1]

[1] P. Hautefeuille and A. Perrey, *Compt. Rendu.* (1888), 107, 1150, and *Zeitschr. f. Kryst.* XVIII (1891), 329.

who recorded its physical properties. This ferric feldspar is, however, unstable and it is a very reasonable supposition that much of the hematite in aventurine feldspars is derived from the decomposition of $KFeSi_3O_8$. As this is a potash feldspar it is perhaps to be expected that it would occur in orthoclasic or microclinic feldspars. The gem orthoclase from Madagascar is perhaps unique, as Wherry notes. The writer's suggestion is that perhaps it contains some undecomposed $KFeSi_3O_8$. The following analyses of this feldspar from Madagascar show, when recast, the probable presence of this potash-ferric component.

The question arises: Has the compound $KFeSi_3O_8$ any bearing on the color of amazonstones?

While the work of the Geophysical Laboratory on the $MgO-Al_2O_3-SiO_2$ system shows no compound $MgAl_2Si_2O_8$, the writer asks whether or not the existence of a magnesium feldspar, stable only in small quantities in the presence of other feldspars, would not explain the occurrence of MgO in many of the analyses?

BARIUM FELDSPARS

In view of Eskola's[1] recent paper it is not necessary that a complete discussion of the synthesis of strontium and barium feldspars be given here. It is sufficient that a summary of the present status of these minerals and their relationships to the more common feldspars be recorded.

Descloizeaux[2] found that some of the lime in plagioclase can be replaced by barium without changing its triclinic character. The work of Ginsberg[3] on the $CaAl_2Si_2O_8-BaAl_2Si_2O_8$ system indicates that anorthite will dissolve a limited amount of the barium feldspar forming a solid solution, and likewise barium feldspar will form a restricted range of solid solutions with anorthite. On this basis we can conclude that the system is a eutectiferous one with limited solubility.

[1] Pentti Eskola, "Silicates of Strontium and Barium," *Amer. Jour. Sci.* (5), IV (1922), 331–75, especially pp. 364–67.

[2] A. Descloizeaux, *Tscherm. Min. Petro. Mitt.*, VII (1877), 99.

[3] A. S. Ginsberg, *Ann. de l'Inst. Polytech. Pierre le Grand à Pétrograde*, XXIII (1915).

Sjogren[1] and Strandmark[2] studied celsian, the latter proving that celsian and orthoclase form an isomorphous solid solution series called hyalophane.

TABLE VI

CASSINITE, BLUE HILL, DELAWARE COUNTY, PENNSYLVANIA

	1	2	3	4
SiO_2	62.60	62.95	62.92	62.91
Al_2O_3	19.97	19.82	20.25	20.28
Fe_2O_3	0.31	0.28	0.20	0.22
FeO	....	....	0.09	0.09
MgO	....	....	0.10	0.11
CaO	0.19	0.25	0.52	0.45
Na_2O	4.31	4.01	3.58	4.03
K_2O	8.95	8.57	9.08	8.86
H_2O	....	....	0.15	0.16
SO_3	....	....	n.d.	0.21
BaO	3.71	3.95	2.78	2.64
SrO	n.d.	n.d.	0.02*	0.02*
Total	100.04	99.83	99.69	99.98

	1 and 2	3 and 4
Orthoclase	53.30	56.05
Albite	36.01	34.30
Anorthite	1.13	2.55
Celsian	9.56	7.00
Sr-Feldspar	....	0.10
Total	100.00	100.CO

* Approximate, spectroscopic determination.

Analyses 1 and 2: Penfield and Sperry, *Amer. Jour. Sci.* (3), XXXVI (1888), 324. See Dana, *System of Mineralogy*, p. 319.

Analyses 3 and 4: Made for the writer by H. B. Croasdale of the Fraser Laboratories, New York City.

Penfield and Sperry[3] have described a barium-bearing perthitic feldspar from Blue Hill, Delaware County, Pennsylvania.[4] Their

[1] Hj. Sjogren, *Geol. Fören. Förh.*, XVII (1895), 578.

[2] J. F. Strandmark, *Geol. Fören. Förh.*, XXV (1903), 289; XXVI (1903), 97; *Zeitschr. f. Kryst. Min.*, XLIII (1907), 89.

[3] S. L. Penfield and Sperry, *Amer. Jour. Sci.* (3), XXXVI (1888), 324.

[4] Dana, *A System of Mineralogy*, p. 319: "A dull bluish-green subtransparent kind, of an aventurine character, from Blue Hill, 2 miles north of Media, Pa., *cassinite*." P. 322: "Cassinite of Lea from Blue Hill, Delaware Co., Penn.; shown by Penfield to be a monoclinic feldspar (extinction on $b = \pm 6°$) with albite running through it in thin tapering plates parallel to the orthopinacoid. The analysis corresponds to 35 p. c. albite, 51 p. c. orthoclase, and 13 p. c. of $BaAl_2Si_4O_{12}$." This formula is incorrect. It should be $BaAl_2Si_2O_8$.

analyses are given in the following tables, together with analyses made for the writer from material supplied by Dr. Samuel G. Gordon of the Philadelphia Academy of Science. As it agrees with the description of the original material there is but little doubt that it is a good representative. Under the microscope it is at once seen to be an intergrowth of a barium-bearing orthoclasic feldspar, hyalophane, and a potash rich albite. Quantitative microscopic measurements[1] resulted as follows:

Phase	Units Measured (Areas)	Spec. Gr.	Product	Reduced to 100
Hyalophane................	17,300	2.555	44,200	68.65
Plagioclase................	7,690	2.6225	20,180	31.35

The distribution of the four components as obtained from recasting Penfield and Sperry's analyses into the two phases must be something like this:

Phase	Per Cent	Orthoclase	Albite	Anorthite	Celsian
Potash.......	68.65	52.20	7.76	0.13	8.56
Soda........	31.35	1.10	28.25	1.00	1.00
Total....	100.00	53.30	36.01	1.13	9.56

This grouping agrees well with the extinction angles:

Potash phase...........(010)....... 18°

Soda phase.............(010)....... 6°

and the specific gravity: 2.692.

The results of recasting Croasdale's analyses can be arranged in a similar manner as follows:

Phase	Per Cent	Orthoclase	Albite	Anorthite	Celsian
Potash.......	68.65	54.46	7.15	.55	6.50
Soda........	31.35	1.59	27.15	2.00	.50
Total....	100.00	56.05	34.30	2.55	7.00

[1] See Part I, pp. 248–59, for an outline of the method used.

Indices of refraction:

Potash phase	α 1.523 β 1.527 γ 1.529
Soda phase	α 1.528 β 1.533 γ 1.535

Extinction angles:

Potash phase	(001)	1.5°–2°
	(010)	6.° –8°
Soda phase	(001)	4.°
	(010)	18.°

We can draw the conclusion that celsian is not isomorphous with any of the plagioclase feldspars, including albite.

STRONTIUM FELDSPARS

Eskola says: "It was . . . . found that the strontium feldspar is, in its optical properties, exactly like the calcium feldspar. . . . . It is . . . . probable that the strontium feldspar forms a complete series of solid solutions with anorthite."[1] He does not state its relation to orthoclase but it is reasonable to expect that it does not form solid solutions with it to any extent. As an illustration of barium and strontium bearing feldspars the following analysis of an albite from Seiland, Norway, is introduced.

TABLE VII

ALBITE FROM SEILAND, NORWAY

Analysis calculated to 100

	Percentage	Recast	
SiO_2	66.87	. . . .	. . . . .
Al_2O_3	20.55	. . . .	. . . . .
CaO	1.04	Albite	87.11
BaO	.11	Orthoclase or microcline	6.20
SrO	.11	Anorthite	5.16
Na_2O	10.27	Celsian	0.26
K_2O	1.05	Sr-Feldspar	0.35
Total	100.00	. . . .	99.08 per cent

[1] P. Eskola, "Silicates of Strontium and Barium," *Amer. Jour. Sci.* (5), IV (1922), p. 367.

TABLE VIII

TABULAR SUMMARY

Minals

Hexagonal	Monoclinic	Formula	Triclinic
....	Orthoclase	$KAlSi_3O_8$	Microcline[1]
....	"Barbierite"	$NaAlSi_3O_8$	Albite
....	....	$CaAl_2Si_2O_8$	Anorthite
....	Celsian	$BaAl_2Si_2O_8$	....
....	....	$Na_2Al_2Si_2O_8$	Carnegieite[2]
Nephelite	....	$NaAlSiO_4$	....
....	....	$SrAl_2Si_2O_8$	Strontium Feld

Series

Minals	Solid Solutions	Intergrowths
Orthoclase-Albite Microcline-Albite	Anorthoclase[3]	Perthite[4]
	Transitional crypto-microperthite	
Albite-Anorthite..............	Plagioclase[5]	....
Orthoclase-Anorthite Microcline-Anorthite	....	Oranite[6]
Carnegieite-Anorthite..........	Anemousite[7]	....
Orthoclase-Celsian............	Hyalophane[8]	....
Plagioclase-Hyalophane........	....	Cassinite[9]
Sr-Feldspar-Anorthite.........	No Name	....
Sr-Feldspar-Orthoclase Sr-Feldspar-Microcline	....	No Name
Sr-Feldspar-Albite............	No Name	....

[1] Microcline. Breithaupt, *Jour. Ch. Ph.*, LX, p. 324. "Triclinic potash feldspar."

[2] Carnegieite. H. S. Washington, *Jour. Geol.*, XVI (1908), 10; H. S. Washington and F. E. Wright, *Amer. Jour. Sci.* (4), XXVI (1908), 187, and XXIX (1910), 52–70, also XXXIV (1912), 555.

[3] Anorthoclase. Rosenbusch, 1886, *Mic. Phys.*, 550. A triclinic soda-potash feldspar resembling orthoclase.

[4] Perthite. Thomsen, 1832, *Shep. Min.* (1), 232. Interlamination of orthoclase and albite. First considered a variety of orthoclase.

[5] Plagioclase. Breithaupt, *Breit. Handb.*, III, 492, General term including several triclinic feldspars.

[6] Oranite. H. L. Alling, *Jour. Geol.*, XXIX (1921), 235. Intergrowth of either orthoclase or microcline and anorthite.

[7] Anemousite. See references under Carnegieite.

[8] Hyalophane. Waltershausen, *Progg. Ann.*, XCIV, 134.

[9] Cassinite. Lea, 1866, *Acad. Nat. Sci. Proc.*, 110. A variety of orthoclase containing barium. Extended by Alling to mean intergrowths of hyalophane and plagioclase. 1923.

CONCLUSIONS

To the conclusions reached in Part I, to which the reader is referred, the following are to be added:

1. The degree to which the potash-soda feldspars undercool, depending upon their origin, renders it impossible to construct a

single thermal-diagram to illustrate the crystallization of the system. Consequently a *series* of diagrams, one for each mode of origin, is necessary. (Fig. 1.)

2. The proof of the dimorphism of $KAlSi_3O_8$ and $NaAlSi_3O_8$ is exceedingly difficult to obtain. The "peg models" of the specific gravities, indices of refraction and extinction angles, suggest two series, one the orthoclase-barbierite and the other the microcline-albite series. No entirely satisfactory series of diagrams that show the dimorphism of both components can be made at the present time.

3. The existence of nephelite in solid solution in feldspars is more common than is supposed. When present it profoundly affects the physical properties, so that determination by microscopic means alone is very uncertain. It may be that the specimen from which barbierite was named is a nephelite-bearing albite.

4. Granting dimorphism, many rapidly cooled feldspars, such as sanidines and orthoclases, possibly may be mixtures of two distinct series: the so-called "monoclinic" series and the "triclinic" feldspars. This sometimes renders determination a difficult matter.

5. Twinning is caused in part by pressure. It may be caused by stress set up by the change in volume accompanying inversion. "Scotch-plaid" twinning is not a reliable criterion for microcline. The writer agrees with Hawes that plagioclase is not always striated, and would put the reader on his guard.

6. The decomposition of the unstable ferric feldspar, $KFeSi_3O_8$, may well account for pink microclines and other aventurine feldspars.

7. Zonal-grown crystals are perfectly normal in rocks cooled at the proper rate. Too rapid cooling prevents zonals while slow cooling allows them to become homogeneous through reaction between themselves and the still unfrozen liquid of the magma.

8. The main contributions are the diagrams giving the specific gravities, indices of refraction, and the extinction angles of the potash-soda-lime feldspars.

ACKNOWLEDGMENTS

The writer is under obligation to many for helpful suggestions, constructive criticism, assistance, and encouragement. Among these he takes pleasure in expressing his indebtedness to Professors

Kemp, Berkey, Campbell, Colony, and Kendall, of Columbia University; Professor A. N. Winchell, of the University of Wisconsin; Professor Albert Johannsen, of the University of Chicago; Professor William S. Bayley, of the University of Illinois; and to Dr. Henry S. Washington and Dr. Pentti Eskola, of the Carnegie Institution of Washington. Dr. S. Kozu, of Tohoku University, Sendai, Japan; Dr. Olaf Andersen, of the Norwegian Geological Survey; Dr. Edgar T. Wherry, of Washington; Dr. Samuel G. Gordon, of the Philadelphia Academy of Science; Mr. George L. English and Dr. A. C. Hawkins, of Ward's Natural Science Establishment, Rochester; and Professor Henry E. Lawrence, of the Department of Physics of the University of Rochester, have also rendered valuable assistance.

ERRATA

Page 285, ninth line from bottom. For "*i* . . . . monoclinictr ⇄ icilinic . . . ." read "*monoclinic⇄triclinic. . . . .*"

Bottom of page 290, for "$KAISi_2O_6+SiO_2 \leftrightarrows KAISi_3O_8$" read:

"$KAlSi_2O_6+SiO_2 \leftrightarrows KAlSi_3O_8$"

Title of Fig. 3, page 291, for "$KAlSi_2O_8$" read "$KAlSi_3O_8$."

Footnotes on page 292 (facing Plate I) belong on page 305.

Page 298 (facing Plate II) Feldspar "I," for "Granite" read "*Oranite.*"

For footnotes on page 305 *see* page 292.

SIGNIFICANT AMELIORATIONS OF PRESENT ARCTIC CLIMATES

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In an article in a recent number of this *Journal*[1] it was found by comparisons of oceanic with terrestrial climates between mid-latitudes and the poles that the present effect of the ocean on climate in those latitudes is cooling rather than warming. It was found further that theoretical considerations lead to the same conclusion. Thus these inquiries disclosed the untenability of the veteran theory that the ancient mild climates of high latitudes are assignable to extension of the ocean in itself alone considered. At the same time, the inquiry made it evident that the sea is a potent climatic influence. This is largely due to its exceptional capacity for storing heat and the facility with which it transfers heat because of its mobility. The data for comparison were so ample and convincing that it was not felt necessary to dwell on the details of the most striking case of climatic amelioration in high latitudes now available for study. This was reserved for special discussion in the present article, because it is singularly well fitted to reveal the really effective sources of such climatic ameliorations. This most instructive case is found at the head of Baffin Bay, in a *land-girt* region on the *west* side of the oceanic thoroughfare between the Atlantic Ocean and the Polar Sea. Because of the relative mildness of its climate and the abundance of its food supplies, this region has been the home of the Arctic Highlanders, a tribe of healthy, vigorous and competent Eskimos, for an unknown period. Theirs is the most northerly permanent settlement of the world at the present time. This habitable land is isolated on all sides by tracts so inhospitable that they are not permanently inhabited by man. It is an oasis in the frigid desert of the north. Its significance stands out when its land-girt

[1] T. C. Chamberlin, "A Veteran Climatic Fallacy," *Jour. of Geol.*, Vol. XXXI (1923), No. 3, pp. 179–91.

situation and its position on the west side of the Atlantic drift are compared with the sea-girt situations of Spitzbergen and Franz Joseph Land in practically the same latitude on the warm side of the Atlantic drift. These islands have no permanent human inhabitants.

South of the land of the Arctic Highlanders and separated from it by an inhospitable tract of two hundred miles, the dreaded Melville Bay, lies a coastal belt of relative mildness occupied by the Danish Colony of West Greenland. While this lies mainly between 63° and 73° N. Lat., scattered settlements reach nearly to the southern point of Greenland, and a single settlement of Eskimos, Angmagssalik, is more or less permanently maintained on the southeast coast. Though this is itself quite isolated, it seems, in a sense, to connect the West Greenland Colony with the settlements on Iceland. The real effect of this feeble connection, however, is rather to relate the climate of Iceland to the climatic mildness in Baffin Bay than to suggest that the latter is a normal part of influences referable to the "Gulf Stream." The district occupied by the Danish Colony of Greenland is a true factor in the singular climatic amelioration on the east coast of Baffin Bay, and will be treated as the more southerly and larger twin of the little oasis at the head of the bay. It is not, however, milder than some other tracts of its own latitude. While the mildness of both these tracts is very notable for their situation and latitude, it is to be understood that these are *Arctic* climates and much more severe than those singularly genial climates implied by the fossils of several geologic stages.

THE SIGNIFICANT FEATURES OF THE GENERAL SITUATION

The most remarkable feature of these districts of climatic amelioration is that they lie northward from the northwest angle of the Atlantic Ocean and reach within 12° of the North Pole. It is especially to be noted that they are not in the great oceanic sweep of the warm Atlantic drift into the Polar Sea. They bear the aspect of offshoots or outliers from *the coldest corner of the Atlantic.* This is emphasized by the further fact that between them and the main warm Atlantic drift there runs the greatest of the Arctic outlets, carrying southward a compact stream of ice-floes from the border

of the polar ice-field. It is therefore important to enter into some detail respecting the essential features of this singular situation.

A broad sea-arm branches off from the northwestern angle of the Atlantic and gradually narrows northwardly until it forms Davis Strait, although even here it has a width of 200 miles (see map, Fig. 1). This narrowing is due to a submerged ridge crossing the sea-arm at this point and linking Greenland to Baffin Land. It is a part of an intercontinental ridge to be described later. Beyond this ridge the sea-arm broadens again and constitutes Baffin Bay, which attains a maximum breadth of about 480 miles, a depth at several places of over 1,000 meters, and stretches onward to about 78° N. Lat. As the bay approaches this high latitude, the lands on the east and west close about it and its bottom shelves up into relative shallowness. A rather narrow channel, Smith Sound, leads on to the northward and connects, through Kennedy and Robson channels, with the Polar Sea. The tide enters the poleward mouth from the north, and the drift of the ice in these channels is southward into the head of Baffin Bay, but this drift is pressed to the right by rotation and keeps mainly on the western side of the bay. Farther south on this western side, Lancaster and Jones sounds join Baffin Bay nearly opposite Melville Bay, into which they project their cold waters. Both these sounds lead back through other narrow channels westward and northwestward to the Polar Sea and are fed by its icy waters, which press into them as though they were outlets. With exceptions of this limited kind, Baffin Bay is land girt. The great island, Greenland, confines it on the east and north; the islands of the American Arctic Archipelago border it on the west. The whole sea-arm takes the form of a long inlet into the broken northeast angle of North America. From its mouth to the head of Baffin Bay, this inlet has a length of about 1,500 miles. Looked at comprehensively, the region is more largely land than sea, although distinctly a combination of the two.

Relations to ice-bearing currents.—The East Greenland ice-bearing current is the greatest of all avenues of discharge of ice-floes and melt-waters from the Polar Basin. Apparently, also, it is the main line of ultimate discharge of the land waters that flow toward the pole. The investigations of Nansen and his colleagues seem to

FIG. 1.—Photographic reduction of map of the North Atlantic Ocean issued by the Institut für Meereskunde der Universität Berlin (1912). Original in colors. Oceanic depth in meters: contours = −100, −1,000, −2,000, −3,000 −4,000 −5,000, −6.000 −7,000, −8,000, over 8,000.

show that the north Eurasian rivers find their ultimate exit from the Polar Basin through it. The procession of ice-floes in the season favorable to it is very compact, and usually hugs the coast of Greenland as far south as Cape Farewell, about which it wraps closely—unless forced off by winds—and, swinging to the northward, crosses the open mouth of Davis Strait and joins a similar ice-bearing current coming from the northward along the coast of Baffin Land. This latter carries ice-floes from the inlets that join Baffin Bay at the north and on its western side, as already stated, together with the local ice of the bay, and the icebergs discharged into it from the Greenland glaciers. These usually move in stately processions southwestwardly across the bay. This Baffin Land current and the great East Greenland current join at the south to form the Labrador current, which is felt as a pronounced cooling influence as far south as the coast of Maine, and less markedly beyond.

It thus appears that the climatic oases under study lie in the fork between two great streams of polar ice-floes and icebergs, while beyond lies the polar ice-field itself.

It is not necessary to urge that the relative mildness under study is due to warm waters coming from somewhere and reaching these oases somehow. That scarcely requires discussion. It appears that such warm waters could ordinarily reach these areas of climatic amelioration only by passing *under* the currents that discharge the polar ice-floes. It does not seriously affect the general truth of this that there may be occasional or seasonal conditions under which warm currents may reach the Danish Colony as surface currents along the coast of Greenland as represented on some charts. I know of no claim that even these reach the northern oasis.

The icy barrier between the northern and the southern oases.—The inhospitable tract which separates the two ameliorated areas apparently owes its origin to the projection into and across Melville Bay of streams of cold waters from the Polar Sea through Lancaster and Jones sounds, which join Baffin Bay on the west opposite Melville Bay (see map, Fig. 1). As already noted, these sounds reach back through connecting channels to the great ice-fields of the Polar Sea, and their mouths in that direction are persistently choked by ice-floes driven into them from the west and north. It is the persis-

tent ice blockade thus formed which has rendered futile so many attempts to force a ship through what would be—but for the ice—a convenient "Northwest passage," though the attempt has been bravely renewed again and again for two centuries. As these polar waters, projected across the Baffin tract, curve about in Melville Bay and begin to move south, they veer to the right, because of the earth's rotation, and so follow the west side of Baffin Bay, leaving opportunity for the rise of warm waters on the east side, where not prevented by the intrusion of these polar streams. Like the other polar streams, these that occupy Melville Bay are surficial; the warm currents that give amelioration to the oasis north of it *pass under it.*

The degree of amelioration of the northern oasis.—Among the familiar evidences of amelioration, it may be noted that the tract north of the inhospitable Melville Bay long ago acquired from explorers the title, "The North Open Water." There is little doubt that the striking nature and persistence of this open water, so far north, gave rise to the dream of an "open polar sea," which for a long time was confidently entertained by some of the early explorers. The freshest testimony as to the openness of this region in winter, from a scientific source, is given incidentally in the discussion of icebergs by Lauge Koch in a recent number of this *Journal.*[1] Koch defines his second class of icebergs as those which break off from glaciers "on an open coast where no sea ice is formed in winter, so that there is no hindrance to the formation of bergs. Of this type are the glaciers of Cape Alexander, in 78° North lat."[2] Cape Alexander lies near the northern edge of the oasis under discussion. Near by it on the north is Etah, an Eskimo settlement that has become widely known from the part it has played in Arctic exploration.

Admiral Peary speaks of this region as "one of the most interesting of all Arctic localities"; and also as "a little oasis amid a wilderness of ice and snow. . . . . Here, in striking contrast to the surrounding country, is animal and vegetable life in plenty,

[1] L. G. Koch, "Some New Features in the Physiography and Geology of Greenland," *Jour. of Geol.*, Vol. XXXI (1923), No. 1, pp. 42–65.

[2] *Ibid.*, p. 53.

and in the course of the last hundred years some half a dozen Arctic expeditions have wintered here."[1]

The singular abundance of the lower life of this region has been the subject of so much surprised comment and vivid description by Arctic explorers and scientific visitors for the last century that there is no need to go into much detail here. There is a well-rounded fauna which embraces long chains of species dependent on one another for support. This implies permanence and steadiness of evolution. These biologic chains reach from great predaceous sea mammals, birds and man, down through many intermediate types to minute orders of sea or land life. It is to be noted that no large part of the life in this region consists of *outre* forms dependent on scant supplies of food and on protection by isolation, as in the case of the Antarctic penguins and like types. The fauna here embraces multitudes of migrant forms of bird life of wide-ranging types which congregate here to feed and to nest. Such large assemblages are the best of evidence of climatic geniality and richness of feeding ground. There is also a large non-migrant element which must of course find food during the winter, and this sufficiency of winter food is in itself an unequivocal form of testimony to the hospitality of the climate.

The life of the tract occupied by the Danish Colony has been quite fully studied, and is set forth in Rink's "Greenland" and in many later papers. It will suffice for this discussion to refer to Seward's recent statement—quoted in the review of his book on *A Summer in Greenland* in a recent number of this *Journal*[2]—to the effect that while not a flowering plant is known in the Antarctic region nearer the pole than 62° S. Lat., more than 400 species of flowering plants grow in Greenland above the corresponding north latitude.

However, notwithstanding this abundance of life, it is to be clearly understood that the present Greenland oases are merely remarkable ameliorations of *Arctic* climates. They are not climates of the warm temperate or subtropical sort, such as are implied by

[1] *The North Pole* (1910), p. 36.

[2] A. C. Seward, *A Summer in Greenland*. Review by T. C. Chamberlin, *Jour. of Geol.*, Vol. XXXI (1923), No. 3, pp. 253–55.

the fossil faunas and floras of these and other high latitudes in certain periods of the Paleozoic, Mesozoic, and Cenozoic eras. The present polar climates are really of the glacial order, and the present epoch is, in my view, to be regarded climatically as a part of the Pleistocene glacial period. The present stage seems to belong to the degree of severity usually called interglacial, though we hope the present stage is to prove *terminal* rather than really *inter*glacial.

THE MORE REMOTE SOURCE OF THE AMELIORATION

It has been indicated already that the mildness under study is due to warm waters that have found their way to these localities notwithstanding their location off the northwest corner of the Atlantic in a region of glaciers and in spite of the polar ice-streams that predominate at the surface and cross the line of connection with the warm regions of the Atlantic. There is no ground to question the immediate agency of relatively warm waters coming to the surface in the ameliorated tracts; our problem lies wholly in the localization of these emergences of warm water and the ulterior causes that actuated them. In the main it is a question of the flow or creep of warm rather saline waters under colder ice-bearing waters which are lighter because less saline. Concretely, the crux of our problem lies in explaining an underflow or undercreep of warm Atlantic waters *to the northwestern corner* of the Atlantic, and sending thence an offshoot 1,500 miles to the northward. Still more specific is the question why so seemingly anomalous a current should be more effective at the head of Baffin Bay than is the broad "Gulf Stream" or "Atlantic Drift" on Spitzbergen or on Franz Joseph Land.

Two factors in the answer have probably already suggested themselves:

1. *Carrying heat under cover.*—The very fact that the warm waters of the ameliorated tracts of Baffin Bay can only, as a rule, reach the place of their appearance at the surface as *undercurrents* suggests that they lost less of the heat they gained in low latitudes on the way than they would if they had flowed at the surface for so great a distance. This factor of transportation under cover will, I think, appear to be one of great importance in some of its

wider applications to be discussed later. It is not that there is great importance in explaining this unique case, but the principle of carrying heat under cover has far-reaching applications in the greater climatic problems of geologic history. Even in this case, as will appear a little later, much more than usual emphasis will be laid on the function of the middle layer, the layer under cover, in bearing warmth to the high latitudes and in promoting that particular phase of oceanic circulation of which the warm undercurrent of Baffin Bay is regarded as an offshoot.[1]

2. *Confinement rather than deployment.*—A second factor that seems to conduce to the special mildness in the areas under study is the degree to which the waters of the warm currents in the Baffin inlet are prevented from spreading and increasing their contact surfaces and thus losing heat and suffering mixture by this increased contact. Baffin Bay occupies a rather narrow, deep trough between lands on either hand. It converges at its head, where the northern oasis lies, and there the warm current seems to be concentrated and

[1] To forestall misunderstanding as to the extent and completeness of the overriding lighter ice-bearing currents near the mouth of Baffin Bay, it is to be recognized that on some charts and in some descriptions a warm surface current is represented as flowing from the Erminger current south of Iceland around the southern point of Greenland and along the east side of Davis Strait into Baffin Bay, but this is to be accepted only in a qualified sense, for the connection of the East Greenland stream of polar ice-floes with the Labrador current and the currents that flow down the west side of Baffin Bay is not only well established but is recognized as a normal and dominant feature of the general system of interchange between the polar and the Atlantic circulations. As I saw this great ice-stream in July, 1894, in what I understand to be its normal state for that season, its complete continuity and its dominance were very impressive, and there could be no question as to the complete exclusion of any warm cross-current at the surface. But the seasons bring variations in the relative strength of the currents, and special winds cause diversions. Some of these special influences may open the way for temporary warm currents at the surface along the west coast of Greenland. Tropical wood, presumably from the West Indies or the tropical coasts of the American mainland, is sometimes found on the coast of the Danish Colony, and this seems at first thought necessarily to imply the continuity of a warm current from the south at the surface, but the evidence is less rigorous than it seems, for floating matter may be shifted from one current to an adjacent one of different type and destination by transverse winds. Though it has seemed necessary to recognize this testimony to an assigned surface current from the warm Atlantic waters into Baffin Bay, it is quite certain that the mild climates of the Danish Colony, and especially of the land of the Arctic Highlanders, are not dependent on breaks in the continuity and dominance of the main ice-streams that serve as outlets of the Polar Sea.

pressed to the surface. This is in contrast to the situations in which Spitzbergen and Franz Joseph Land lie. There the warm currents from the south are not only permitted to spread, but the opening of the connecting tract into the Polar Sea seems to require this. Though these islands stand in the broad avenue through which the "Gulf Stream" or the "Atlantic Drift" flows toward the Polar Sea, they necessarily suffer from the spreading of the warm waters over a broad surface and their consequent cooling. Though these waters appreciably warm the tract traversed, the effect is insufficient to maintain such a persistent hospitality and such prolific life as does the unique little tract at the head of Baffin Bay. This is a striking verification of one of the theoretical conclusions offered in the last article.[1]

The remaining problem.—But giving to these two factors all that is due them, the anomaly of a climatic oasis within 850 miles of the North Pole and on the cold side of the oceanic thoroughfare between the Atlantic and the Polar Sea is not yet adequately explained. There is little ground to expect to reach any such explanation without analyzing the modes of oceanic exchange between the producing sources of warm water and of cold water, respectively, which involves that of saline water, on the one hand, and fresh water, on the other. This requires attention to the configuration of the Polar and Atlantic basins in which the opposite kinds of water are generated, as also of the intervening thoroughfare through which the exchange of these waters takes place. It is a step of some consequence to recognize definitely that there are two dominant areas of generation and a connecting tract between them. The connecting tract is often rather loosely regarded as a part of the Atlantic Basin, or else as a part of the Polar Basin, but it is better to regard it as neither. Functionally, it is a connecting avenue *defined at either end by partially submerged intercontinental ridges; these ridges serve at once as dams and as weirs.* Between the ridge-dams and weirs at either end there is an uneven tract occupied by basins, shallows, and islands. The parts of this tract that most concern us in this discussion are the Norwegian and Berentz seas,

[1] "A Veteran Climatic Fallacy," *Jour. of Geol.*, Vol. XXXI (Feb.-Mar., 1923), pp. 179–91.

and the deeps, shallows, and islands connected with them, though the region to the east as far as the New Siberian Islands and beyond is involved. It is not necessary, however, to dwell on the intricate details of circulation in this connecting tract, except so far as it affected the interchange between the generating basins on either end, for the gist of our present problem centers in the Polar Basin, where cold waters are generated, and in the Atlantic Basin, where warm waters are generated. Let us, therefore, look upon the connecting tract merely as an oceanic thoroughfare with ridge-dams and weirs at either end. There is so little exchange through the channels of the American Archipelago and through Behring Strait that these may be neglected here.

THE INTERCONTINENTAL RIDGES

The Southern Intercontinental Ridge.—The more southerly of the partially submerged ridges that connect Eurasia and North America has for its best-known section the Wyville-Thompson Ridge, but this is merely the most exploited sag in a much greater feature. The ridge is continuous from the Wyville-Thompson sag southeastward through the British Isles to the European continent, and northwestward through the Faroes, Iceland, Greenland, Davis Strait, and Baffin Land to the American continent. This Southern Intercontinental Ridge has, at present, more critical climatic bearings on the Atlantic-Polar exchange than the Northern Ridge, because its lowest notches have less depth and give a shallower weir or a higher dam as one chooses to look at it. It is, of course, to be kept in mind that the exchanging waters pour over this weir in *both* directions as they do at the Straits of Gibraltar, the Dardanelles, and many other such weirs. The greatest depth of water over this Southern Ridge thus far disclosed by soundings is 314 fathoms, or about 600 meters, but the exploration is as yet incomplete.

The Northern Intercontinental Ridge.—Separated from the Southern Intercontinental Ridge by about 20° latitude is the Northern Intercontinental Ridge, connecting the northerly border of the Eurasian continent, by way of Franz Joseph Land, Spitzbergen, North Greenland, and Grinnell Land, with the northern islands of the American Archipelago and the northern border of the American

continent. This ridge lies near the edge of the two continents and not far back from the abyssal portion of the Polar Basin. The bordering flat between the ridge and the basin has about the usual width, depth, and aspect of a continental shelf. The deepest submerged notch in this ridge seems to lie between Spitzbergen and Greenland, but it has not as yet been positively defined by soundings. The difference between the abyssal waters of the Norwegian Sea and those of the Polar Basin, however, make the existence of a defining weir of this kind practically certain, and fix the maximum depth of water over it at about 3,000 meters. As well brought out by Nansen and others, these two ridges, acting as weirs, determine the upper boundary of the abyssal waters in the Polar Basin and in the Norwegian Basin, respectively, and through this determination they indirectly fix the depths attained by the currents or layers of water formed by the circulation above the abyssal waters.

So far as known, the inlets through the American Archipelago into Baffin Bay and Hudson Bay are too shallow to be occupied by any but the upper currents flowing out of the Polar Basin; this statement may, however, be found to need revision. It is wise to bear in mind that canyon-like channels across barriers like these partially submerged ridges that serve as weirs may easily excape the sounding-lead, especially when soundings are few. And more than that, such canyons may once have existed but were filled afterward and may now be quite indetectable. The shallow Behring Strait plays only a small part relatively in the exchanges between high and low latitude and need not be considered in this discussion.

One of the notable effects of the Southern Intercontinental Ridge is that it holds the surface of the cold saline abyssal waters of the Polar Basin a thousand meters or more above the surface of similar abyssal water in the mid-Atlantic as now determined. As the less dense layers of water developed above these heaviest abyssal waters yield to them, and must conform to them in both basins, this great difference is a radical feature. It implies that in seeking an interpretation we should proceed on the assumption that the superabyssal water-strata of the mid-Atlantic, taken together, are much thicker than the corresponding layers of the Polar Basin. This greater depth is well established for the tracts of the mid-Atlantic,

whence the warmer upper and middle layers originate. This is especially true of the outpour from the Mediterranean later to be discussed. Near the great intercontinental dam over which the waters pour in both directions, much mixing and irregularity of motion and constitution is to be expected, and present data are quite inadequate for a discussion of details. Here, however, the general fact of a difference in thickness of the polar and the Atlantic water-columns will perhaps suffice. At any rate, this difference between the polar and Atlantic columns is only a striking intensification of what should arise normally in less degree in all similar cases, for the polar water-column should be relatively thickest in its cold, dense, basal layer and the Atlantic in its warm, saline layer, and these dominant layers should actuate the circulation so far as dependent simply on temperature and salinity. A comparison of the two columns is thus a necessary step toward interpreting the great features of the polar-Atlantic interchange so far as dependent on density, and density is the radical feature of oceanic circulation. Let us then consider these two columns, bearing in mind, however, that the layers of water are not stationary, but moving; that they are not fixed in temperature and salinity, but always changing toward equilibrium.[1]

THE THREE MAIN LAYERS OF THE COLUMN OF THE POLAR SEA

From the determinations of Nansen[2] and others it appears that a typical column of the waters of the Polar Basin from surface to bottom embraces three main layers:[3]

[1] The data from which these generalized comparisons are made have been gathered chiefly from Murray's well-known publications, particularly the *Challenger Reports*, *The Ocean Depths*, and *The Ocean;* the papers of Nansen and associates, particularly *The Scientific Results of the Norwegian North Polar Expedition* (1893–96); Jenkins' *Textbook of Oceanography* (1921); and James Johnstone's "Oceanography," *Enc. Brit.*, new Vol. XXXI (1922).

[2] "Norwegian North Polar Expedition," *Scientific Results*, Vol. III.

[3] Nansen gives four layers, but for the present general discussion the distinction between the two upper, rather thin layers seems immaterial as both are cold layers of less than mean salinity, and have a common origin in surface conditions. These two layers are thus defined by Nansen:

"(1) A surface-current of water with low salinity (from about 29 o/oo to about 33 o/oo, perhaps 20 or 30 m. deep, running towards the northwest and west;

"(2) An underlying, slow current of water with a higher salinity and a very low temperature, running in a different direction, and consisting of surface water from other parts of the Polar Sea. The absolute minimum of temperature is situated in this current, at about 50 or 60 m."—*Ibid.*, Vol. III, p. 346.

1) *An upper layer* of very cold water whose salinity is relatively low (ranging from 29 to 32 parts per thousand in the more surficial portion, and somewhat higher in the bottom portion) and whose density, because of this low salinity, is less than that of the warmer but more saline layer next below. This upper layer is the source of the ice-laden outlet streams of the Polar Sea previously mentioned. The freshening water which reduces the salinity of this layer comes from precipitation on the sea surface, from the drainage of adjacent lands, and from the melting of ice.

2) A middle layer of warmer but more saline and denser water. Its salinity ranges from about 35.1 to 35.3 parts per thousand (Nansen).

3) *A bottom mass*, very much thicker than both the foregoing layers taken together, and denser than either, because it is both cold and saline. It is the abysmal water of the Polar Basin. So far as known, it occupies all the basin but the upper 800 to 1,000 meters. Nansen gives its mean salinity as 35.29 parts per thousand; in other words, it is slightly more saline than the middle layer. Its mean temperature is about 1.56° C., which is not so low as the basal portion of the upper layer. It holds notable quantities of the atmospheric gases, which implies that even these basal waters take part in a cyclic motion that has its contacts with the air at some stage. They are not stagnant waters, although their motion is probably very slow.

THE SOURCES AND RELATIONS OF THE LAYERS

The two variables by which the waters of the ocean are distinguished are temperature and salinity. The variations of temperature are functions of insolation and radiation and, in a general way, vary with latitude. The variations of salinity depend on the excess or deficiency of precipitation over evaporation, which, is in turn dependent on the ascent or descent of the regional atmosphere. The mean salinity of the ocean is usually taken as about 35 parts per thousand. The salinity varies also with latitude, but in a different way and with greater departures from the general rule. In the very high and the very low latitudes, precipitation generally exceeds evaporation, and the sea-waters suffer dilution. In a belt between these, conveniently known as the 30° belt, evaporation is generally

greater than precipitation, and the sea waters suffer increase of salinity. The distribution of these areas of dilution and increase of salinity are subject to much modification that must be specially considered in any given case. The real cause in the main is the ascent or descent of the atmosphere.

1. *The source of the upper layer.*—There is practically no ground for doubt that the upper layer of water of the Polar Basin is derived from the upper layer of the Atlantic waters with the addition of the excess of precipitation of the region, the inflow from adjacent lands, and the melting of the ice. As the mean dilution of standard sea-water caused by these fresh waters is of the order of 15 per cent, it is clear that the main source of salinity is in the Atlantic waters, whose salinity reaches and in some parts passes the mean salinity of the ocean.

2. *The source of the middle layer.*—There is no doubt that this layer also comes over the intercontinental ridges from the Atlantic, for that is the only assignable source for its combined salinity and warmth, but there is a rather vital question as to the particular part of the Atlantic column from which it comes. This layer is described by most writers as though it had occupied a surface position in the Atlantic, as also when it passed over the Southern Intercontinental Ridge, but that it became cooled and sank to its present middle position later. If by this it is intended to affirm that these middle waters of the Polar Basin are those that formed the "Gulf Stream," or strictly surficial waters of the Atlantic, there appear to be two objections to it: (*a*) the salinity of the middle layer in the Polar Basin (35.1 to 35.3 per mille—Nansen) seems too high to have suffered surface dilution while it was drifting 3,000 miles into a zone in which precipitation is greater than evaporation; and (*b*) if the Gulf Stream—or the surface layer under any other name—sinks to form this middle layer of the Polar Basin, what source remains for the upper layer in the Polar Basin? It seems more consistent with all the considerations that weigh in the case to regard this middle polar layer as a northward extension of the similar *middle* layer of the Atlantic which will be described later. In a loose sense, this middle polar layer may be regarded as a part of the "Atlantic

Drift," if that term is understood to include all the warm waters that flow north over the intercontinental ridge, whether in strictly surficial or deeper levels, but the middle layer of the Polar Basin can scarcely be assigned to the Gulf Stream if that term is confined, as it apparently should be, to such surface waters as were scarcely normal in salinity when they left the Gulf of Mexico and afterward traveled 3,000 miles in zones where precipitation is generally greater than evaporation. These considerations will take on more force when compared with the middle Atlantic layer discussed later.

3. *The source of the bottom layer of the Polar Sea.*—The thick abysmal mass of cold saline water which forms the bottom layer in the Polar Basin is assigned by Nansen to the cooling of the middle layer by contact with colder water. That the bottom layer is derived in some way from the waters above seems quite beyond question, for the Southern Intercontinental Ridge cuts off the cold abysmal waters of the Atlantic and there seems no other source for the low temperature than the surface effects of the Polar climate. But the view that the middle warm layer was cooled to the requisite degree by any form of simple contact with the upper waters seems incompatible with the observed salinities. The mean salinity of the abysmal mass is given by Nansen as 35.29 parts per thousand. The mean salinity of the warm middle layer is slightly less than this, and the salinity of the cold waters of the upper layer is notably less than this. Any simple commingling of the two upper layers should give too low salinity to the lowest layer. Nansen holds with good reason that the bottom waters should be heated rather than cooled from below, and gives observational evidence in support of this. He also holds that the lower part of the upper layer, which is colder and more saline than the uppermost portion, arises from freezing at the surface. Freezing, as is well known, forces out of the forming ice the larger part of the salts and gases previously held in the congealing water. This salt added to that in the layer of water next below gives it higher salinity. Sometimes it rises to the quality of a brine. At the same time it gives coldness, which is sometimes intense. Nansen, however, is inclined to limit these effects of freezing to his second layer—that is, to the lower part of what is here called the upper layer. He thinks that a small and slowly formed

film of brine would be unable to sink through the warm layer next below and give rise to the cold abysmal layer at the bottom.

So far as concerns such freezing as may take place on the under side of the *thick* Arctic ice already formed, this view seems well taken, for the freezing beneath the thick ice, even in the Arctic regions, is slow and limited in amount. The layer of briny water formed by it is thin and subject to mixture while in the process of forming, for more or less of motion between the ice mantle and the water below arises from tides and winds.

But there is a *special* type of freezing action that is much more rapid, while at the same time the film of brine it forms is subject to prompt downward, edgewise propulsion. This requires a careful study of details.

A combination of rapid freezing, brine formation, and downward propulsion.—While freezing under the cover of thick ice that generally mantles the Polar Sea is slow, very rapid freezing takes place in the cold season where open lanes of water are formed rather suddenly by the action of winds and tides. According to Peary and other explorers who have traversed the Polar Sea in the freezing months, the opening of such lanes is frequent and often sudden. Just where and when they will open cannot be foretold, and they are often so swift in action that it is wise to sleep prepared for a possible plunge into the icy waters of the opening chasm. The lanes are often so wide and long as to constitute a most serious obstacle to reaching the pole over the ice-fields of the Polar Basin. Peary describes these lanes or "leads" as being "sometimes mere cracks," "sometimes just wide enough to be impossible to cross," and "sometimes rivers of open water from half a mile to two miles in width, stretching east and west farther than the eye can see."[1] He says that the old floes which are traversed by these "leads" are not simply the products of freezing in place but are formed by the crumpling, crushing, and piling up of such original ice by the almost irresistible power of the great polar ice-sheet, or

[1] Robert E. Peary, *The North Pole* (1910), p. 197. Peary's narrative of his trip to and from the pole (pp. 236–85), gives a very realistic impression of the frequency and extent of the formation of these "leads," and especially of the formidable nature of the "Big Lead," formed over the edge of the continental shelf, in which Marvin lost his life.

some large part of it, when put in motion by winds or tides or both combined. He gives the thickness of the old floes traversed by the "leads" as ranging from less than 20 to more than 100 feet. On the important point of the relative proportion of the ice-field exposed by the lanes to rapid freezing, he writes:

> At least nine-tenths of the surface of the Polar Sea between Cape Columbus and the Pole is made up of these floes. The other one-tenth, the ice between the floes, is formed by the direct freezing of the water each autumn and winter. This ice never exceeds eight or ten feet in thickness.[1]

It thus appears that in the course of the cold season of each year about 10 per cent of the surface of the Polar Basin may freeze in the way subsequently described, or in the course of ten years the whole surface or its equivalent may so freeze.

Peary's narrative shows that even in March and April these leads form suddenly, and that the temperature of the air at the time is often 40° below zero; it shows further that high winds are then frequent and strong. The offsets of the trails recently made by the explorers indicated that differential movements of the ice-mantle were taking place and were considerable in amount.

Putting the significant items together, it appears that the water-lanes formed in the old ice-floes must be bordered by ice-walls on either side whose vertical faces range as high as 100 feet. The larger part of these vertical faces are below the surface of the water and form bounding walls to the water that arises into the chasm as it opens. Thus the water that fills the lane stands above the common mass below as a raised block or prism. It is the surface of this raised prism of water that is exposed suddenly to very low temperature and often to wind action at the same time. The surface must therefore freeze very promptly, whether it is still or is agitated. More or less agitation is apparently the more common case. If agitated by wind, the surface water should form a sludge of mixed forming ice and residual water. This residual water should be charged with the salts forced out of the frozen portion of the water. This is added to the previous content of salt, giving rise to a brine. The sludge thus formed when the wind is blowing will be driven *edgewise* over the surface until it encounters the vertical ice-face

[1] *Op. cit.*, pp. 195–96.

that borders the lane. Here the ice of the sludge is likely to be packed and piled up at the surface while the briny water within it has no alternative but to turn downward along the face of the wall of ice at the edge of the lane. The sludge thus driven forward and separated into packed ice and brine exposes new water behind which undergoes the same process, so that the movement edgewise is constant until the surface is sheeted over with ice thick enough to suppress the waves raised by the wind and bring on a new form of action, to be discussed below. When the edge of the sheet of brine is turned downward in front of the bordering ice-wall, the push from behind continues as long as the wind pushes the water or its motion continues by momentum. This push is edgewise, that is, in the line of least resistance. It is also in the line in which it is itself impelled to go by its density, which is greater than that of the adjacent water. Here then is a combination of push and pull in the line of least resistance, which is felt so long as the force of the wind is felt by the freezing surface.

It seems reasonable to assume that the briny sheet, once it is turned downward at its edge and projected in that direction, will continue downward, for that is the direction demanded by its density as well as its temporary momentum. Now it is not necessary that this action should continue long, for if the brine sheet moves forward and downward no more than 800 to 1,000 meters—which is often less than the width of the lane—its forward edge will have crossed both the upper and middle layers and have entered the basal layer.

This briny layer, while not great in volume, will be exceptionally cold as well as saline, and will carry both low temperature and high salinity into the basal layer, thereby adding little by little the qualities it requires to correspond to its observed characteristics. These little increments will be added here and there, for the lanes open at haphazard, and the briny sheets are driven in to the basal layer at haphazard intervals of both space and time. They will thus be favorably distributed for mixture and diffusion. The abysmal mass is itself in motion, for, as Nansen has shown, it is a current, though probably a very slow one. The action, however, continues year after year for a long period, so that the combination is favorable to an ultimate homogeneous mass.

Perhaps, at first thought, this process will seem to involve the destruction of the warm middle layer, and its existence may seem to be a reason to doubt the verity of the process. The middle layer is of course constantly disappearing by the process but is disappearing only little by little very locally where crossed by the briny film. The middle layer is, however, a *current*, and is being continually renewed. It may thus be preserved, though continually suffering loss. The detail of the operation is important to a clear view. The thin, cold, briny sheet in passing down across the middle layer of course exchanges temperatures and salinities with it at the immediate contact surfaces, but very little elsewhere. This exchange gives the contact portion of the middle layer greater density than the main portion of that layer, and hence this contact film tends to go down with the briny layer and become part of the basal layer rather than remain as a cooled portion of the middle layer. The rest of the middle layer thus retains its temperature almost unmodified. The gradual loss thus sustained by the middle layer is supplied by onflow as a mass from the original source, that is, as interpreted below, from the Atlantic middle layer.

The more special phase of the action has been here described. There is a more general phase. After the surface of the water in a lane freezes over, the vertical walls that border the lane remain, as a rule, until the new ice is crushed by the closing of the lane. So long as the prism of water in the lane thus lasts, any movement of the ice over the water, or of the water under the ice, almost necessarily forces any briny film that may have formed on the top of the prism by continued freezing to move edgewise and thus to encounter the border wall and be turned downward, much as in the previous case. Now, the winds and tides are almost always causing differential movements between the ice-cover and the water on which it floats, and so this downward, edgewise, penetrating action may not be so speci l as it seems.

Atmospheric confirmation.—An interesting atmospheric abnormality has been observed in Grinnell Land by Moss and in Greenland by Krogh, which falls in with this view of salt concentration by freezing and seems to rather pointedly confirm it. These observers, quite independently and at different dates, noticed that when the wind at the localities of observations came from the northwest,

the direction in which the assigned freezing action is supposed to be most effective, the amount of carbon dioxide in the air often rose very notably, sometimes reaching double the normal amount or even more.[1] The most plausible explanation of such an enrichment in carbon dioxide in lands of low temperature where rapid decay is out of the question and where volcanoes are unknown, is the inference—in itself almost a necessary one—that the cold water of the Polar Sea is, as a rule, highly charged with carbon dioxide at all times because of its coldness, and that the freezing of such charged water in the lanes forces out the larger part of this high content of carbon dioxide into the briny layer formed by such freezing, and that a portion of this excess charge escapes into the air, as required by the law of gaseous equilibrium.

THE THREE MAIN LAYERS OF THE ATLANTIC COLUMN

For the purposes of a comparison with the waters of the Polar Sea, the waters of the Atlantic, though more markedly differentiated, may also be grouped into three layers analogous to those of the Polar Basin, an upper, a middle, and a bottom layer. This parallelism is not only convenient for our study, but the three divisions represent the great factors in the oceanic circulation of this region so far as these depend on density, which is the chief cause of oceanic stratification other than surficial wind action.

1. *The upper layer* has considerable diversity. Its chief factors are (*a*) poleward-moving, warm surface currents, and (*b*) equatorward-moving, cold surface currents. These, however, do not cover the whole surface. There are besides, (*c*) surface sheets, the salinity of which is being increased by evaporation, and this increase tends to cause them to sink into the middle layer, so that they are surface layers only in a transient sense. There are also, (*d*) waters that well up from below and bear the nature of lower layers until they have been "weathered" into surface layers. The last two are instructive in that they represent the system of interchange between the upper and lower layers and the process of transition from the one to the other. The first two are the normal surface sheets.

[1] Moss, "Notes on Arctic Air," *Proc. Royal Dublin Soc.*, Vol. II; Krogh, "Abnormal CO_2 Percentage in the Air of Greenland," *Meddelser on Greenland*, Vol. XXVI (1904), pp. 409–11.

a) The Greater Gulf Stream.—The best-known portion of the warm, poleward-moving surface currents has long been called, with some looseness, the "Gulf Stream." For the general purposes of this discussion, it will be convenient to acknowledge this looseness frankly by using the broad term, the "Greater Gulf Stream," which implies there is a narrower sense. Under this broad term let us include all warm surface currents which directly or indirectly unite in carrying heat into the polar regions. This great group may be said to start with the warm, equatorial currents that flow northwesterly along the northern coast of South America, gathering as they go the fresh waters of the Amazon, the Orinoco, and other rivers of South America, as well as the direct precipitation of the rainy region they traverse. They are both warm and diluted. For the larger part they enter the Caribbean Sea and through it reach the Gulf of Mexico. In passing through these bodies they receive further dilution from the rivers of the bordering coasts, notably the great rivers of the Mississippi Basin. As is well known, the configuration of the coasts turns these equatorial waters about to the northeast and they issue from the gulf as the Florida current or the true Gulf Stream.

A part of the equatorial current, however, turns to the northeast outside the Antilles and flows more or less parallel to the true Gulf Stream until the two become practically indistinguishable from each other.

While the Gulf Stream is moving northeasterly near the coast of North America, it appears from the maps of salinity (see Fig. 2)[1] to become rather suddenly much more saline than it was in the Gulf of Mexico, and this holds measurably true far to the northeast. The map of salinity probably requires much revision in detail to represent the specific facts, for the data for a map of salinity are as yet very imperfect. Murray's chart is here accepted in its essentials, with the presumption that fuller data will modify it in important particulars. On Figure 2 it will be seen that there is notable westward extension of the area of high salinity that centers in the heart of the great evaporating tract, or, in other words, the Sar-

[1] Sir John Murray, *The Ocean*, Plate III (in colors). This is reproduced in colors as a frontispiece in J. T. Jenkins' very recent (1921) *A Textbook of Oceanography*. Figure 2 of this article is a photographic copy of this.

FIG. 2.—Photographic copy of Murray's "Map of the Surface Salinity of the Ocean," *The Ocean*, Plate III. Actually taken from frontispiece to Jenkins' *Textbook of Oceanography* (1921).

gasso area. A slight amount of the increase in the salinity of the Gulf Stream east of North America may be assigned to excess of evaporation over precipitation in crossing "the 30° dry belt," but the amount of this seems insufficient to explain the salinity represented on Murray's map. The data seem to imply that there is a reciprocal action between the saline waters of the main evaporating or Sargasso Basin and the adjacent edge of that part of the Gulf Stream which circles about it, by which the two classes of water are intermingled or interdigitated. The waters of the Gulf Stream proper are the fresher and lighter; the waters of the Sargasso region are constantly growing more saline by reason of excess of evaporation over precipitation. Under these conditions an interaction of the two types of waters is likely to take place, assuming the form of spiraloid currents subordinate to the main movement of the encircling Gulf Stream. There would naturally attend this an intermixture or interweaving of waters of a complicated digitate, gyratory sort. This view gains not a little support in the anomalous drifts of wreckage. While the Gulf Stream has a very definite northeasterly movement in this region, the drifts of wreckage are often very strangely at variance with it in details. These peculiarities imply that the Gulf Stream, when studied in detail, is far from being a simple, straightaway current. It seems to be affected by whirls and various anomalous movements of a minor sort. The singular northeastward extensions of the 26°-per-mille salinity line (see salinity chart, Fig. 2), at about 20° West Long. in mid-ocean, fall in with this view. This feature seems rather clearly to imply that the edge of the saline waters of the evaporating area are involved in the northeastward movements of the adjacent Greater Gulf Stream. At any rate, this view seems best to fit the distribution of supersaline waters compared with subsaline waters of the mid-Atlantic, so far as now known. We shall return to this subject in considering the middle stratum of the Atlantic column.

When a little past the middle of the Atlantic, the Gulf Stream sends off a southward, recurving branch, which flows around the east end of the Sargasso area and connects with the North Equatorial current and thus at length completes the loop about the Sargasso Basin. It is important here to note also that, on its outer

side, this loop of the Greater Gulf Stream gives off a branch into the Mediterranean Basin, and that out of this branch of the Gulf Stream group there arises later by evaporation the lower Mediterranean stratum, which in turn forms part of the *middle* layer of the Atlantic waters. This I shall emphasize later. The point is that here is a declared case of the passage of the upper layer consisting of one type of waters into a middle layer of another type of waters, and this middle layer later plays an essential part in the explanation of polar ameliorations here offered, and in later applications of a more general nature.

The main branch of the Greater Gulf Stream flows onward to the northeast, and greatly affects the climate of northwestern Europe, as is well known. A large portion of the Gulf Stream passes over the Southern Intercontinental Ridge, and in the tract between the two intercontinental ridges is much modified by branchings, interdigitations, whirls, and various irregularities. Passing on over the Northern Intercontinental Ridge, this much modified stream, as here interpreted, forms the main source of the upper layer of the Polar Sea described above. We will return to this last point in connection with the middle Atlantic layer.

All this group of currents, here called for convenience the Greater Gulf Stream, are surficial, warm, and rather low in salinity, except as their salinity is increased by interchanges and interdigitations with waters of the adjoining saline layers.

b) The cold currents of the polar outflow.—Over against these warm, surficial waters flowing poleward, stand a group of cold polar currents flowing southward. Their primary source is in the ice-field of the surface layer of the Polar Basin. These are gathered into the Labrador current as their main trunk stream at the south. These occupy the surficial position of the Atlantic column on its west side, corresponding in that respect to the Greater Gulf Stream on the east side. The two may be regarded as the complements of each other. The climatic function of the one is to carry heat northward; that of the other is to carry cold southward. But this is done at great loss, for both are surficial. Moreover, their waters, instead of being altogether the same throughout their journeys, are constantly changing by intermixture with other waters as a part of

the tendency ever present to move toward an equilibrium of salinity and of temperature.

When the Labrador current encounters the Gulf Stream at the eastern angle of the American continent, formed by Newfoundland, great irregularities and interdigitations of current are developed and its further course becomes obscure.

c) The surface concentration of salt.—The foregoing warm northward-going and cold southward-going currents receive practically all the fresh waters shed from the adjacent lands. They also receive nearly all of the fresh waters that fall in areas where excess of precipitation over evaporation prevails, and practically all the melt waters of the Arctic ice-floes and icebergs. Taken together, they embrace nearly all of the surface waters that are much subject to dilution. This dilution is the chief reason why they remain surface waters.

Over against these areas of surface dilution stand the areas in which evaporation exceeds precipitation and the surface waters grow more and more saline. This increasing salinity adds to their density and gives them a tendency to descend, so that, while it is necessary to recognize that, for the time being, they are surface waters, and so in a formal sense part of the upper strata of the Atlantic column, they are really the initial stage of a lower layer composed of more highly saline and hence denser waters even though they remain warm. The evaporating areas center on "the 30° dry belt," but this belt is crossed by storm tracts near the western border of the Atlantic, chiefly in the gulf region. Nearer the center of the ocean a large area is developed in which descending air prevails rather persistently, and evaporation is notably in excess of precipitation, the Sargasso area. In addition to the Sargasso area in the mid-Atlantic, the Mediterranean region is a marked area of concentration of salt by evaporation. It is the more distinctive because it is isolated from the ocean except for its slender connection through the Straits of Gibraltar. It is a peculiarly instructive type. The saline waters of these two tracts will be further considered in connection with the middle Atlantic layer to which they give rise.

d) The upwelling areas.—It is only necessary merely to mention these tracts here for the sake of completeness. They are smaller

than the foregoing, and are mainly secondary to movements in other parts of the ocean body. In their natures these waters belong to the deeper layers from which they come.

The middle Atlantic layer.—The origin of the middle layer of the Atlantic column is most clearly illustrated by the transformation that takes place in the isolated basin of the Mediterranean. As previously noted, a side current from the southward-flowing branch of the Gulf Stream west of Spain enters the Straits of Gibralter and forms the upper layer of the Mediterranean in its western portion. As it creeps eastward, its salt content is concentrated by evaporation in spite of the fresh waters that flow into it from the adjacent lands. By the time it has reached the east end of the Mediterranean, it has attained a salinity of 39 parts per thousand. In spite of its warmth this salinity gives it a density sufficient to make it sink and creep back westward as the bottom layer. This at length flows out into the Atlantic as a bottom current in the lower part of the Straits of Gibraltar. On entering the Atlantic, it sinks by reason of its saline density through the upper oceanic waters, and spreads out in delta fashion, until it reaches a depth of about 2,000 meters, where its base finds a horizon of equilibrium. On its left hand, it has been traced about 10° southwestward. On its right hand, it pushes northwestward and has been detected as far as 52° to 53° N. Lat., or half way to the mouth of the Baffin Bay inlet. Beyond this point, data are so scant as to leave its further extension obscure. It seems probable that it merges on the west with the similar waters rendered saline by evaporation in the Sargasso area and that the two together make up a true middle layer distinct from that below by reason of its warmth, and fairly distinct from that above by its higher salinity, though, of course, it is constantly grading into the contact waters above and below, by various forms of commingling and diffusion.

A portion of the middle layer, in this large and general sense, appears to creep southward to compensate, in part, for the surficial equatorial waters shunted into the North Atlantic by Cape St. Roque, while another part creeps northward to maintain, by interchange according to the laws of equilibrium, the salinity of the northern waters. Waters of adequate salinity must obviously flow into

the northern regions to account for the fairly close approximation of the middle and bottom layers of even the Polar Basin to the mean salinity of the whole ocean. The concentration of salts by excess of evaporation over precipitation is the sole dependence of any moment for offsetting the dilution of the tracts where precipitation is greater than evaporation. The high latitudes belong to this latter class of areas, and adequate saline waters must flow into these regions to maintain the observed salinity of their waters.

As the weir formed by the Southern Intercontinental Ridge, though not yet fully explored, has a water depth of about 600 meters at least, there is room for a warm, saline middle current as well as the somewhat diluted and cooled surficial current—the Gulf Stream factor—to flow over it poleward. Both classes of water are recognizable in the Norwegian Sea beyond. The only point of present divergence from current opinion—if indeed there is really any at all—lies in the assignment of the partially diluted and somewhat cooled waters flowing over the weir northward to the Gulf Stream group, and in the assignment of the more saline and warmer class of waters going over the weir *to the middle layer* which better preserves its warmth and salinity because it flows *under cover*.

The bottom Atlantic layer.—Where the Mediterranean layer of warm saline water pours out in delta form into the Atlantic, it forms a well-defined middle layer. This gives place below at about 2,000 meters' depth to a still heavier layer which is both saline and cold. This fills the abyssal depths of the whole Atlantic Basin, and similar waters occupy the depths of all the oceans. These abyssal waters of the Atlantic are of the same type as the bottom waters of the Polar Basin. They are thought to be derived from them in part at least, for this seems to be the only adequate line of outflow, for the abyssal waters of the Polar Basin and, as noted before, their nature seems to show that they are a part of a persistent and effective circulation. The abyssal waters of the North Atlantic seem, as present data stand, to be more saline and heavier than those of the more southerly oceanic basins. They should hence tend to flow outward toward these in part also; this would tend, in turn, to offset the surficial waters shunted into the North Atlantic by Cape St. Roque. This interchange would help toward the equaliza-

tion of the salinity of the whole ocean which, in the long run, must be preserved. All our postulates seem thus to tend to general equilibrium and at the same time recognize the excess of evaporation over precipitation in the North Atlantic drainage area taken as a whole.

THE APPLICATION OF THE FOREGOING TO THE SPECIAL CASE IN HAND

The purpose of the foregoing rather wide-ranging discussion is to bring out the general features of circulation from which the ameliorating current of Baffin Bay is derived by a natural rather than a strained hypothesis. In itself, the Baffin Bay branch is a small affair, but its peculiarities make it refractory to the usual line of interpretation. It is hence suggestive and significant. As a feature of the "Gulf Stream" or of the northeasterly "drift of the Atlantic" surface waters as ordinarily understood, the localization of the warm Baffin Bay current diverges from ordinary oceanic modes of movement. Its line of projection is northwestward from the center of generation of the warmth and salinity it carries poleward, while the normal direction due to the influence of the earth's rotation is northeastward. Yet the rotational influence is as obvious on this current as on others, after it has entered Baffin Bay. The rotational effect is of course always active, but in the massive movement of the deeper part of the middle layer of the Atlantic Basin it is overcome by co-operating influences now to be noted. As a slow undercurrent in the embrace of currents of different trend above and below, and as a mere offshoot from the great middle layer of the Atlantic column, its explanation takes on a special phase dependent on these conditions. In the region where it is generated, the middle Atlantic layer is 2,000 meters thick, *less* the depth of the Greater Gulf Stream that floats above it. The true Gulf Stream, as it is crowded through the Florida Straits, is credited with a depth less than a third of this, and as it spreads out in the higher latitudes its depth is undoubtedly still less. The middle layer, as here interpreted, thus extends much below the crest of the weir formed by the Southern Intercontinental Ridge. This ridge stands *obliquely athwart* the natural line of northeastward flow of the warm middle

and upper Atlantic layers in their normal circulatory courses. Only the upper layer (the Greater Gulf Stream) and the upper part of the middle Atlantic layer are permitted to flow directly on over the obliquely set weir. The lower part of the thick middle layer is shunted to the northwest by the oblique attitude of the weir.

A natural effect of this oblique divergence by an intercontinental dam whose side is much buttressed by submerged ridges is more or less of tortuous and rotational subcurrents, some of which should appear at the surface in more or less modified forms. This effect should be cumulative toward the west side of the weir or the northwest corner of the Atlantic, in other words, the angle between the oblique weir and the east coast of North America. Indications of this shunting and the incidental deformation of currents and distributions is shown on the accompanying salinity map (Fig. 2), especially to the south and the southwest and west sides of Iceland and off the mouth of the Baffin Bay inlet. The climatic conditions of Iceland are in themselves very suggestive, for Iceland is far toward the western end of the weir and on the west side of the Atlantic. It is, moreover, at that end of the weir over which the cold polar waters pour in going southward. On the same salinity chart, but farther from the axis of the ridge-dam and obviously controlled by the south-projecting point of Greenland, is a notable loop of the salinity curves toward the mouth of Baffin Bay. These, to be sure, are surface features, but they probably represent and depend upon a deeper movement. They definitely suggest the divergence of an undercurrent such as that which gives rise to the striking ameliorations of climate in Baffin Bay. Such an undercurrent shunted into the Baffin Bay trough offers a very natural explanation of the singular way in which the East Greenland polar current of lighter ice-laden water curves so sharply about the southern point of Greenland and is carried northward in crossing the mouth of the Baffin Bay trough, because the latter floats on the former and is carried in due degree along its course.

With such intimate relations to much colder and less saline waters, the Atlantic offshoot into Baffin Bay becomes reduced in temperature and in salinity in its 1,500 mile advance to the head of the bay, but still it gives striking evidence of being more effective

climatically when it is forced to the surface at the head of the bay than is the more direct surficial Gulf Stream when it reaches the same latitude in Spitzbergen.

The lessons of the study seem to be (1) the superior climatic efficiency of undercurrents compared with surface currents, (2) the superior potency of the middle layer of the Atlantic. (3) The effects of confinement compared with spreading are also pointedly illustrated but in reality the results are more a matter of form than of real quantitative effect when the sum total of climatic influence is considered.

THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION AND MAGMATIC DIFFERENTIATION OF IGNEOUS ROCKS

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VIII

THE TEMPERATURE-INTERVAL OF THE CRYSTALLIZATION OF THE IGNEOUS ROCKS

We will take as the starting point for the calculations in this chapter the determinations made at 1 atmosphere pressure (in water-free melts) of the minerals, the eutectics, the mix-crystals, the liquidus- and solidus-curves, etc.

We will then have to make two corrections: (*a*) on account of the effect of pressure, and (*b*) on account of the effect of light volatile compounds dissolved in the magma (H_2O, CO_2, etc.).

As explained in an earlier chapter[1] the melting points of the silicate minerals increases with the pressure, but only in a *relatively* insignificant degree. In flows, for instance, we have to deal with only 2.5° or at most 10° C., and even in deep-seated rocks crystallized at very great depths, the rise of the temperature may be only about 25 or 50° C. Hence the effect of pressure is practically out of the question. But not so with the effect of H_2O, CO_2, etc., to which we will return below.

As typical examples of *anchi-monomineralic rocks*[2] we will choose the *anorthosites and the peridotites*. The solidification of $Ab_m\ An_n$ (without any admixture of foreign materials), according to Bowen's investigations, in water-free melts at 1 atmosphere pressure, takes place at the following temperature-intervals, when we assume

[1] This *Journal for* 1922, p. 611–614.

[2] In a later paper I shall try to prove that these rocks must have crystallized from ordinary, thoroughly melted magmas. I cannot agree with Bowen's exposition of the anorthosites as formed in a kind of magma-gray with large quantities of plagioclase-crystals and in addition a magma in subordinate quantity.

complete equilibrium between the solid and the liquid phase as in the case of most deep-seated rocks:

	Start	End
$Ab_1 An_5$	1521°	1465°
$Ab_1 An_2$	1490°	1372°
$Ab_1 An_1$	1450°	1287°

With incomplete equilibrium the crystallization of the final melt would have taken place at a somewhat lower temperature.

In *anorthosites*, with only 4–10 per cent of pyroxene, olivine, iron ore etc., the last mentioned minerals, according to *Bowen's* diagram for the system Ab : An : diopside, will occasion only a relatively small reduction of the temperature for the beginning of the crystallization of the plagioclase. The relatively small quantity of end-magma in these rocks, will at a late stage of the solidification crystallize along a eutectic boundary-line (or plane) at a much lower temperature, about 1225–1200°.

For the various anorthosites poor in foreign minerals (calculated at 1 atmosphere pressure and assuming water-free melts) we will have the beginning of crystallization in the bytownite rocks at about 1475–1500°; in the relatively An-rich labradorite-rocks, with $Ab_2 An_3 - Ab_1 An_2$, at about 1450°; and in labradorite-rocks, with about $Ab_1 An_1$ at about 1400°. Following this, the main part of the plagioclase will crystallize at a little lower temperature, down to or a little below 1300°. Finally, comes the crystallization of a small quantity of end-magma at a somewhat lower temperature, about 1200°.

For *dunite*, consisting chiefly of an iron-poor olivine (most frequently about 0.09 Fe_2SiO_4 . 0.91 Mg_2SiO_4, sometimes even with as little iron silicate as 0.075 $Fe_2 SiO_4$. 0.925 Mg_2SiO_4) with a small percentage of picotite, chromite, bronzite, etc., the crystallization[1] must have started at as high a temperature as 1500°. With very little admixture of foreign minerals and at the same time with an olivine especially poor in iron, the temperature may have been a little higher, as 1550–1600°. The main part of the crystallization will take place at a temperature higher than 1400°, and

[1] Cf. this *Journal* for 1921, Fig. 22, p. 522.

only a small quantity, existing as a eutectic end-magma, at some lower temperature.

A great part of the crystallization of other peridotites with much olivine (most frequently between 0.10 $Fe_2\ SiO_4 \cdot 0.90\ Mg_2\ SiO_4$ and 0.15 $Fe_2\ SiO_4$. 0.85 $Mg_2\ SiO_4$) and a little more bronzite, diopside or diallage, etc. (mostly 15–40 per cent) than in the first case will have taken place at a high temperature, about 1400°. The same is also true for bronzite rocks.

We will now discuss the most important *anchi-eutectic* rocks.

As a starting point for *the gabbros* and *the norites*, we have the eutectic boundary-line determined by *Bowen* between Ab+An and diopside, with temperatures (as before at 1 atmosphere pressure and in water-free melts) from about 1260° for 51 diops. : 49 $Ab_1\ An_4$ to about 1215° for 28 diops. : 72 $Ab_7\ An_3$. If we substitute ordinary iron-bearing hypersthene or diallage for the iron-free diopside this will result in the lowering of the above-mentioned temperature but not to any specially important degree. Most gabbros and norites contain a small surplus above the eutectic boundary, in some cases of plagioclase and in others of a ferro-magnesian silicate. Hence the crystallization will most frequently commence at 1250° or 1275°, and the main part crystallize along a eutectic boundary at about 1225–1200°. For some gabbros and norites, diabases, basalts, etc., however, we will have to assume a still lower end temperature. These values, calculated from the physico-chemical diagrams (for water-free magma at 1 atmosphere pressure) are confirmed by an experiment made by Sosman and Merwin[1] concerning the melting of a diabase from Granton, New York: "The remelting begins at about 1150° and is practically completed somewhat below 1300°. The rock flows readily at a temperature about 1225° at which temperature all is fused excepting about a third of the feldspar. A little feldspar still remains undissolved at 1250°, but only traces remain at 1300°."

The *diorites*, owing to the somewhat higher per cent Ab in the plagioclase, must have a little lower crystallization-interval than

[1] *Jour. Wash. Acad. Sci.*, III (1913). See also Day, Sosman, and Hostetter (*op. cit.*), *Amer. Journal. Sci.*, XXXVII (1914).

the gabbros and norites. The difference, however, cannot be very important.

The syenitic rocks.—According to precision investigations at the Geophysical Laboratory in Washington, the melting-point of pure Ab (Na $AlSi_3O_8$) or, to be quite exact, of 98 Ab+2 An, is 1100°±10°. Dr. Arthur L. Day of Washington, recently wrote me that, for pure Or ($KAlSi_3O_8$) we will have to count on about 1200°, "a full hundred degrees higher than that of albite,"[1] but that precision-determinations are extremely difficult owing to the high viscosity.

The Norwegian mineralogist, Th. Vogt, in a speech in Christiania Videnskapsselskap, April 16, 1920—after the first section of this work had already been sent to Chicago for publication—analytically defined the binary system Or : Ab more closely,[2] and further established the fact that we here have to deal with a mix-crystal eutectic system. The eutectic is situated at about 40 Or : 60 Ab (or perhaps 35–40 Or : 65–60 Ab), without possibility of giving the figures of the binary eutectic quite exactly.

According to some investigations made in 1912 by E. Dittler,[3] which, however, are only approximatives and not precision determinations, mixtures of Or and Ab show a lowering of the melting-point, which is greatest, namely almost 50°, at about 45–40 Or : 60–55 Ab, that is, close to the binary eutectic between Or and Ab as determined by the analytic-petrographic working method.

My young friend Olaf Andersen (from Christiania), formerly in the Geophysical Laboratory of Washington, told me that he proved, by investigations made in Washington but never published, that there is a lowering of the melting point for average

[1] In my explanation in this *Journal*, 1921, pp. 335–39, I assumed that Or had the same melting-point (1100°) as Ab. This is not quite a correct assumption. However, this has only a quite insignificant influence on the given view in the section just mentioned. (Written in the Winter, 1921–22.)

[2] My earlier analytic determination (in my treatise in *Tscherm. Min. Petr. Mitt.*, 24 [1905], about 40 (or 40–44) Or: 60 (or 60–65) Ab or Ab+An, do not count for the binary system but represent the eutectic boundary curve between Or and Ab+An at the presence of 10–25 per cent quartz etc.

[3] *Tscherm. Min. Petr. Mitt.*, 31, 1912.

mixtures of Or and Ab at about 50° below the melting point of Ab. On account of the extreme viscosity of the melts, it, however, was impossible to determine the exact lowering of the melting point.

It is to be noted that *Or and Ab* form a *mix-crystal-eutectic* whose melting point lies near 1050° (or some degrees above 1050°). We further notice that orthoclase crystallized in eruptive rocks (predominantly composed of an average mixture of Or and Ab which crystallized at a temperature only a few degrees below the melting curve between Or and Ab,) can take up by the temperature of the formation at least 55, possibly even 58 per cent or a little more Ab. On the other hand plagioclase crystallized under similar circumstances can absorb at least 25–30, and probably even a little over 30, per cent Or. In the crystallization of igneous rocks consisting of predominant Or+Ab with a quite subordinate admixture of ferromagnesian silicates, etc., there will therefore only be a very little jump chemically between orthoclase very rich in Na $AlSi_3O_8$ (Bröggers soda-orthoclase or soda-microcline) and albite or other plagioclase very rich in $KAlSi_3O_8$[1] (Rosenbusch's anorthoclase). When the two feldspars are formed at lower temperatures, the solubility in the solid phase of Ab in orthoclase (or microcline)

[1] I find it unnecessary in this very short résumé, which is based on Th. Vogt's lecture (April, 1920), and which I myself have completed with some further studies, to quote the numerous previous treatises on the very important problem here treated. I shall only mention a treatise by E. Mäkinen, Helsingfors, "Über Alkalifeltspäte" (*Geol. Fören. Forh.*, 1917), and by R. Herzenberg, "Beitrag zur Kentniss der Kalinatronfeltspäte" Diss. Kiel, 1911. H. A. Alling (see this *Journal* for 1921, No. 3) believes that "both the potash and the soda feldspars are dimorphous, each existing in two isomeric forms: each component crystallizing either in monoclinic or triclinic modification, depending on the temperature and the viscosity of the magma, that orthoclase and albite are high-temperature modifications and that microcline and possibly (?) barbierite are relatively low-temperature forms." This supposition cannot, however, be correct. The explanation advanced by Michel-Lévy, and later adopted and proved by Mallard, Rosenbusch, Groth, and Brögger, namely that orthoclase only is a cryptolamellic microcline, has now been given final proof, in that orthoclase and microcline show an identical Laue-diagram (Hadding, "Röntgenographische Untersuchung von Feldspat," *Lunds Universitets Aarsskrift*, Vol. XVII, 1921). And the mineral barbierite, a monoclinic soda feldspar consisting of $NaAlSi_3O_8$ with only small admixtures of Or and An, is no doubt based on a mistake.

and of Or in plagioclase (albit-oligoclase, oligoclase, etc.) is very remarkably diminished, as may be illustrated by the following:[1]

	Temperature of Formation	Percentage of	
		Ab (or Ab+*An*) in Orthoclase	Or in Albite Oligoclase-Albite, Oligoclase
Granite.............	About 900° (or 850°)	About 33	About 13
Granitic pegmatites..	About 700° (or 750°)	About 30 (28)	About 10
Aplite veins.........	About 300–400°	Adularia about 15	Albite about 5
Low temp...........		About 10	About 3 (?)

Most of the proper syenites—hence not including the nepheline- nor quartz-syenites—contain Or and Ab+*An* in proportions between 55 Or : 45 Ab+*An* and 30 Or : 70 Ab+*An*. That is, some have a relatively small surplus of Or, and others a similar relatively small surplus of Ab+*An* above the eutectic boundary between Or and Ab+*An*. In numerous syenites we find almost precisely the eutectic proportion of Or and Ab+*An*.

The binary eutectic between Ab and Ca Mg Si_2O_6, according to the investigations of *Bowen*,[2] lies at almost 100 per cent Ab and very little Ca Mg Si_2O_6. The extreme viscosity renders a precise determination impossible, but by extrapolation only a small (2 or 3) per cent Ca Mg Si_2O_6 might be estimated. The eutectic between Na, K-feldspar and aegirite—or a point on the eutectic boundary curve between Ab+Or and Na Fe Si_2O_6 with a little Ca Mg Si_2O_6 etc.—consists of

2.5 p.c. aegirite
97.5—Na, K-feldspar

(66 Ab with a trifle An and 34 Or).

This agrees with petrographic experience, viz., that the ferromagnesian silicates (augite, amphibole, biotite, etc.) when their quantity in the syenites amounts at least to a small per cent (say

[1] See my treatise on the "Physikalisch-Chemische Gesetze der Krystallisationsfolge in Eruptivgesteinen," *Tscherm. Min. Petrogr. Mitt.*, XXIV (1905), pp. 528–42; further C. N. Warren, "A Quantitative Study of Certain Pertitic Feldspars," *Proc. Amer. Acad. of Arts and Sci.*, Vol. LI (1915), and Mäkinens' treatise of 1917.

[2] Amer. Jour. Sci., XL (1915).

6, 5 or perhaps even as low as 4 or 3 per cent) begin to crystallize at an earlier stage than the feldspar.

As little as 2 or a very few per cent of ferromagnesian silicate in the eutectic may only insignificantly diminish the temperature of the crystallization (as for instance 10 or 25°).

The conclusion is that the crystallization of syenites, in most cases containing only 5, 10 or up to 15 per cent of ferromagnesian silicates (presuming 1 atmosphere pressure and anhydrous melts) may have begun at about 1100°—in some cases up to about 1150°—and that the final solidification of the end-magma took place at a temperature a little below 1050°.

A small, as 2 to 6 or 8, per cent of quartz in quartz-gabbros, -norites, -diorites, or -syenites will bring about only a slight lowering of the temperature at the beginning, but a greater lowering at the close of the crystallization because there finally will result a granitic eutectic.

The granitic rocks.—Because the *binary* eutectic Or : Qu and Ab : Qu contains a considerable quantity (about 26 or 28 per cent) of quartz, we have to deal here with a decided lowering of the melting point, namely, 100° or a little more (as 125°) below the melting point of the given feldspar.[1] If the effect of pressure is left out of the question, the Or : Qu eutectic must be estimated at about 1100° or 1075°, and the eutectic Ab : Qu at about 1000 or 975°. For the *ternary* eutectic, Or : Ab : Qu, a temperature about 100° (or 125°) lower than for the binary eutectic Or : Ab, must be assumed, consequently about 950 (or 925°). The An contained in the plagioclase will occasion some increase in the temperature, but this rise is relatively small, since the plagioclase in the granites (albite-oligoclase, and oligoclase) as a rule only contains a small quantity of An.

Most granites (with 70–75 per cent SiO_2) contain between 20 and 28 per cent quartz, hence a little less or just about as much quartz as the eutectic boundary-line between quartz and K-feldspar +Na-rich plagioclase. Very rarely are the granitic rocks, including the quartz-porphyries and related rocks, so rich in silica that they contain even a small surplus of quartz above the eutectic.

[1] See p. 336 (and Fig. 3) in this *Journal* for 1921.

The relation between Or and Ab+*An* in granitic rocks lies with a few exceptions within the boundaries 0.7 Or : 0.3 Ab+*An* and 0.2 Or : 0.8 Ab+*An*. In about half of the heretofore published analyses[1] the proportions vary within the rather narrow boundaries, 0.5 Or : 0.5 Ab+*An* and 0.35 Or : 0.65 Ab+*An*. For a very large number we find almost exactly 0.4 Or : 0.6 Ab+*An*. The other components, besides quartz comprise a small percentage of Mg+Fe -silicates, magnetite, etc.

A very large number of the granitic rocks, chemically, lie very close to a complicated eutectic, Qu : Or : Ab+*An* : about 1 per cent ferromagnesian silicate and about 1 per cent magnetite, etc. The melting point,[2] when the temperature is recalculated to one atmosphere pressure and when H_2O, etc., is not taken into consideration, is not higher than about 950°, probably between 950° and 900°.

A small percentage of Mg+Fe-silicate, magnetite, etc., above the just mentioned complicated eutectic, will only raise the beginning of the crystallization a few degrees. A surplus of feldspar, in some cases orthoclase (microcline), in others a plagioclase rich in soda,—will raise it a small amount, say 50° or thereabouts. Hence, the crystallization in the most common granitic rocks (without a surplus of quartz), calculated at 1 atmosphere pressure and without regard to the H_2O, etc., of the magma, will not have begun at a higher temperature than 1000°, or, for rocks especially rich in Or, perhaps as much as 1050°. Most granitic rocks must have been quite fluid even a little below 1000. The conclusion of the crystallization will have taken place at a maximum of 950° and probably between 950° and 900°. In rocks with more than 75 or 76 per cent silica, the relatively small amounts of quartz present in surplus above the decisive eutectic, will raise the temperature of the beginning of the crystallization a little above the temperature of the

[1] As to the analyses published up to a few years ago, I refer to the statistic view—including about 600 analyses of granitic rocks—given in my treatise, *Anchi-monomineralische und anchi-eutektische Eruptivgesteine*, 1908, p. 75.

[2] Instead of melting *point* it should here, where the plagioclase as well as the ferromagnesian silicates are mixcrystals, be written: "A short distance on a eutectic boundary-line or-plane."

eutectic boundary line between Qu and the feldspars, but since the ordinary granitic rocks do not contain any significant surplus of quartz, the rise will be rather small.

We will now give a review of the temperatures (calculated at 1 atmosphere pressure and without regard to the contents of H_2O, etc., in the magma) at the beginning of crystallization of the silicate minerals for a number of igneous rocks.

Anchi-monomineralic rocks.—

Dunite........................About 1500°, occasionally 1550–1600°
Other peridotites with less olivine..About 1400°

Bronzite rocks...............About 1400°
{ Labradorite rocks............About 1400–1450°
{ Bytownite rocks.............About 1475–1500°

Anchi-eutectic rocks.—

Gabbro and norite.............About 1250°
Diorite......................About 1200°
The most common syenites....About 1100°
The ordinary granites..........About 1000° (in part a little less)

We will here have to make two corrections: The pressure will occasion a rise, while the H_2O, etc., content on the other hand, will cause a lowering of the temperature of crystallization. The effect of pressure in lava flows may practically be neglected, and even in deep-seated rocks at 5 to 10 km. depth, the effect is very insignificant (see my treatise in this *Journal* for 1922, pp. 611–14). Even though the pressure of 5 to 10 km. depth raises the beginning of the crystallization of one mineral say 10°, and another say 40°, the difference between these figures is unimportant.

Different, however, is the effect of the light volatile compounds, H_2O, CO_2, etc., since these, when present in a noteworthy amount, lower the temperature of the crystallization remarkably. This lowering is nearly proportional to the amount of H_2O, CO_2 etc., in the same magma.

The content of H_2O, CO_2, etc., in the magmas of anorthosite, dunite, bronzite-rock, and other petrographically related anchi-

monomineralic[1] rocks, must, as explained in an earlier paper[2] generally, both absolutely and relatively, have been very little. We will, therefore, get only a small lowering of the temperature of crystallization on account of H_2O, CO_2, etc., in these rocks). Since the anchi-monomineralic rocks are always characterized by the presence of a mineral with a rather *high* melting temperature—such as labradorite, bytownite, olivine, orthopyroxene, diopside poor in iron, further nepheline, leucite, ilmenite, etc.,[3]—in so rich a quantity (as at least about 90 per cent) that the other components only bring about a rather small lowering of the melting point, the result will be that *these anchi-monomineralic rocks generally have a high temperature for the beginning of the crystallization, and this temperature is considerably higher than for the anchi-eutectic.*

Regarding the temperature of the *conclusion* of the crystallization, for instance in anorthosite and norite, on the other hand, we will have fair identity. There is this difference, however, that the eutectic end-magma of the anorthosites is present in a small quantity, while that of the norites is present in considerable abundance.

As we shall explain in a later paper, the high temperature at which the magmas of anorthosites and peridotites start to crystallize has a very important geological significance, because in my opinion, this causes these rocks never to appear as effusives, and causes the anorthosites—probably the dunites too—to be formed only in very deep-seated magma-basins.

For the *anchi-eutectic* magmas we may suppose a somewhat larger content of H_2O, CO_2, etc., and this content, as explained earlier[4] must have been relatively large, especially in the deep-seated *granitic* magmas.

[1] The sulphide ore segregations of typus Sulitjelma and Röros will not be considered here because these, as to the physico-chemical conditions of the genesis, occupy a separate place. See my résumé-treatise, *Die Sulfid-Silikatschmelzmassen*, 1918, p. 245, and the detailed description by Th. Vogt in his monography on "Sulitjelma" (*Norw. Geol. Survey*, now being printed).

[2] This *Journal*, 1922, p. 667–668.

[3] Here is not taken into consideration the segregation of nickel-pyrrhotite, with a relatively low melting temperature.

[4] See this *Journal*, 1922, p. 670–71.

Th. Vogt, in the lecture above quoted (April 16, 1920) in Christiania Videnskapsselskab, mentioned that the contents of light volatile compounds ordinarily must have been smaller in the effusive magmas than in the corresponding deep-seated magmas. Because the pressure increases the melting or the crystallization temperature much less than the volatile compounds lower it, therefore the deep-seated rocks in general, with perhaps some exceptions, will have crystallized at some lower temperature than the corresponding effusives.

Even if we do not consider the contents in the magmas of the light volatile compounds, the granitic magmas will show a lower temperature for the beginning of the crystallization than the magmas of any of the other more common rocks. Since we must assume that there is a larger amount of H_2O, CO_2, etc., in the granitic rocks than in the analogous magmas of the other more common rocks, we may draw the conclusion that *the granitic rocks are characterized by lower temperature for the beginning of the crystallization than are the other rocks*, perhaps with the reservation that there may be some rare igneous rocks of small extent where the temperature of the solidification is just as low or perhaps even a little lower than that of the granitic rocks.

R. A. Daly[1] states, "that the ordinary granites have been at least partly molten at a temperature no higher than 870°, nor lower than 575°." The first mentioned figure (870°) applies to the point of inversion between tridymite and α-quartz, but this point increases very remarkably with the pressure.[2] Consequently, the point of inversion determined at 1 atmosphere pressure cannot be used as a geological thermometer. The point of inversion between α and β quartz (at 1 atmosphere pressure = 575°) seems on the other hand to increase only very little with the pressure.[3] In this way we get a lower boundary at the conclusion of the crystallization.

The interval of the crystallization of granite-magmas—presumed waterfree and at 1 atmosphere pressure—is calculated to be between

[1] *Igneous Rocks and Their Origin*, 1914, p. 214.

[2] See this *Journal*, 1922, p. 620.

[3] See this *Journal*, 1922, p. 619.

about 1000° and 900°. In deep-seated magmas we will get a small addition to this, say 10–50° on account of the pressure, but on the other hand, a greater subtraction on account of the light volatile compounds. Therefore the crystallization will probably not have started at a higher temperature than about 950°, and for the relatively H_2O-rich anchi-eutectic magmas (delivering biotite and muscovite) we will probably have to count on only 900°. The conclusion of the crystallization may have taken place at a little lower temperature. The solidification of the granite therefore lies at about 900°; probably, for many granites even a little lower, say between 900° and 800°.

As to the granite-pegmatite dikes, with relatively large quantities of the light volatile compounds in the magma we will have to count on still lower temperatures; estimated by Th. Vogt at about 700°.

The great difference in the temperatures of the solidification of different igneous rocks can be illustrated as follows: two-thirds or three-fourths of an anorthosite magma solidifies at a temperature at which a gabbro-magma is still quite fluid, and a quartz-free gabbro is completely solidified at a temperature at which a granite magma has not yet started to crystallize (perhaps not considering the beginning of crystallization of certain telechemic minerals such as apatite, zircon, pyrite, etc.).

We will in conclusion point out the following: 1. The granites have the *lowest melting or crystallization temperatures* of all igneous rocks (at least of all the more common rocks). 2. As an end-product by the solidification of *quartz*-bearing gabbros, norites, syenites, etc., there results a *granitic* magma, which has often burst forth in the form of special dikes. 3. Granites belong to the *last epoch of the eruption* in the great petrographic provinces.

Points 2 and 3, as will be explained in a later paper, are due to the fact that magmas containing Qu as a special component (corresponding to more than about 55–60 per cent SiO_2 in the total rock) give by a differentiation of crystallization, according to our physico-chemical melting-diagrams, *a granitic magma* as the *end-product.*

On account of the physico-chemical facts we may draw the conclusion that this end-magma is characterized by a relatively

low temperature of crystallization. That this is true we have proved above in an empirical way.

We may note at the same time that a granitic magma, according to its history (as will be more fully explained in a later paper), *can never have been overheated above the upper boundary of the interval of the crystallization.*

Any hypothesis based on one hundred degrees or more of overheating of the granitic magma above the temperature at which the solidification began, must be rejected as unmaintainable.

THE TEMPORARY MISSISSIPPI RIVER[1]

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CONTENTS

ORIGIN OF THE TEMPORARY MISSISSIPPI RIVER

The temporary Mississippi River referred to in the literature by Leverett,[2] Udden,[3] Carman,[4] Norton,[5] and others and published on the "Preliminary Outline Map of the Drift Sheets of Iowa, 1904,"[6] owed its existence to the displacement of the pre-Illinoian Mississippi by the Illinois glacial lobe which pushed its way westward into eastern Iowa.

[1] Published by permission of the director, Iowa Geological Survey.

[2] F. Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey, Mongraph XXXVIII* (1899), pp. 89–97; "Outline of Pleistocene History of Mississippi Valley, *Jour. of Geol.*, Vol. XXIX (1921), pp. 615–26.

[3] J. A. Udden, "Geology of Muscatine County," *Iowa Geol. Survey*, Vol. IX (1899), pp. 257–58, 350–57; "Geology of Louisa County," *op. cit.*, Vol. XI (1901), pp. 63–64, 108–9.

[4] J. Ernest Carman, "The Mississippi Valley between Savanna and Davenport," *Illinois Geol. Survey, Bull. 13* (1909), pp. 57–63.

[5] W. H. Norton, "Geology of Scott County," *Iowa Geol. Survey*, Vol. IX, 1899.

[6] *Iowa Geol Survey*, Vol. XIV (1903), Plate III.

DESCRIPTION OF COURSE OF THE TEMPORARY MISSISSIPPI RIVER

The advancing Illinoian glacier in crossing into Iowa from the east blocked the valley of Mississippi River and filled it with ice, damming the waters of the great river and necessitating the finding of a new course to the west. The stream found an opening by way of the Maquoketa River Valley and flowed first westward then southward through Goose Lake channel to the valley of Wapsipinicon River, and finally over the low divide between Mud and Elkhorn creeks to the valley of the Cedar at Moscow. Thence, continuing southward to the junction of Iowa and Cedar rivers at Columbus Junction, the combined waters of Mississippi, Maquoketa, Wapsipinicon, Cedar, and Iowa rivers, and those flowing from the edge of the ice, found their pathway obstructed on the one side by the great ice wall of the Illinoian ice sheet and on the other by the Kansan bluffs which stand 120 to 140 feet high. As the waters were unable to find an outlet, they rose and formed a large lake. Finding a low divide at Columbus Junction, the surplus water flowed by a devious course to the valley of Mississippi River below Fort Madison.

The course of the temporary Mississippi River is best described under the following heads: (1) Goose Lake channel, (2) Mud–Elkhorn–Mud Creek Valley, (3) Cedar River Valley between Moscow and Columbus Junction, and (4) abandoned channel south of Columbus Junction.

GOOSE LAKE CHANNEL

Goose Lake Channel (Fig. 1), which was first described by McGee,[1] comprises the northernmost part of the temporary Mississippi Valley and lies between Maquoketa River on the north and Wapsipinicon River on the south. The valley is well defined and ranges in width from one to approximately two miles. The valley walls, especially in the northern half, are cut into bedrock and rise from 70 to 200 feet above the flat valley floor, except toward the southern end, where they rise only about 25 feet. At the present time, Goose Lake channel is occupied by two small streams, Deep

[1] W J McGee, "The Pleistocene History of Northeastern Iowa," *U.S. Geol. Survey, Eleventh Ann. Rept.*, Part I (1899), p. 392.

Creek flowing north and Brophy Creek south, and in both cases, the creeks are very small in proportion to the size of the valley. The valley occupied by one stream continues across the very gentle divide at its head into that of the other without any constriction or in any way losing its identity. The divide between the two creeks, which has an elevation of about 670 feet above sea level, is so flat and poorly drained that a large marsh, formerly Goose Lake, covers its surface. Were it not for the fact that the creeks are seen to flow in opposite directions a divide would not be suspected.

Exposures in the channel are extremely few and those seen consist chiefly of horizontally stratified sand covered by loess. According to Carman,

> The surface material of Goose Lake valley passes downward into fine sand which is 60 to 100 feet thick on the divide south of Goose Lake. Farther north in Secs. 17, 8 and 5 of Deep Creek Township, Clinton County, several wells go 110 to 120 feet in sand and fine gravel. In the south part of the channel south of Elvira, wells 70 to 80 feet deep do not reach rock.[1]

MUD–ELKHORN–MUD CREEK VALLEY

For a distance of about fifteen miles westward from the south end of Goose Lake channel the temporary Mississippi River followed the valley of Wapsipinicon River to the debouchure of Mud Creek. This portion of the valley bears no particular name and calls for no special comment.

The name Mud–Elkhorn–Mud Creek Valley is applied to that part of the temporary Mississippi River course which lies between the mouth of Mud Creek on the north and the junction of Elkhorn–Mud Creek and Cedar River on the south, a distance of approximately thirty-six miles (Fig. 1). Like the Goose Lake channel, this valley also contains two insignificant streams, one flowing to the north and the other to the south. As the divide between the creeks in the Goose Lake channel is imperceptible and ill drained, so is that between the headwaters of Mud and Elkhorn creeks in the Mud–Elkhorn–Mud Creek Valley. Several large ponds and marshes cover its surface. It has an elevation of about 725 feet

[1] J. Ernest Carman, "The Mississippi Valley between Savanna and Davenport," *Illinois Geol. Survey, Bull. 13* (1909), p. 57.

above sea level. A noteworthy feature of the northern Mud Creek Valley is that the wide valley floor extends up into the tributary valleys so that the latter are exceptionally wide near their mouths. "It is believed that these broad flood plains (of the tributaries at their mouths) were filled from the main channel rather than aggraded by their own creeks."[1] The valley is not narrowed at the divide. A short distance from the divide the Elkhorn Creek Valley is divided by an island-like ridge into two branches, one trending southwest and the other more directly south. The first, which is the more conspicuous, has a direct course for more than two miles and a width of half a mile. Its valley walls are well developed and sharply outlined. The other branch, though wider, is less well defined and is more circuitous. West of Durant, where the branches reunite, the valley is well outlined for seven miles and ranges in width from a mile and a half to a little over two miles. It unites with the larger valley of Cedar River at Moscow. The valley walls, although more sharply defined at some places than others, merge gradually into the conspicuous feature of the valley, a wide terrace. The surface of this terrace is flat, and it is continuous except where crossed by the narrow valley of Mud Creek, 30 to 45 feet below the terrace surface.

Numerous exposures of sediment are found along the terrace banks of the southern Mud Creek between Moscow and Durant. The deposits seen in the various outcrops are of a uniform character. In the eastern half of the valley the sediments consist of finely laminated silts or clays, whereas in the western end of the valley the deposits are made up of fine stratified sands.

CEDAR RIVER VALLEY BETWEEN MOSCOW AND COLUMBUS JUNCTION

Between Moscow, Muscatine County, on the north and Columbus Junction, Louisa County, on the south is the unusually wide valley of Cedar River (Fig. 1). This valley is an extensive lowland surrounded on all sides by drift uplands which rise above it to the height of 80 to 100 feet. Its length is 24 miles and its width 5⅛ miles. The valley is characterized by uninterrupted, wide, and monotonously even terraces, the upper surfaces of which

[1] W. H. Norton, "Geology of Scott County," *Iowa Geol. Survey*, Vol. IX (1899), p. 415.

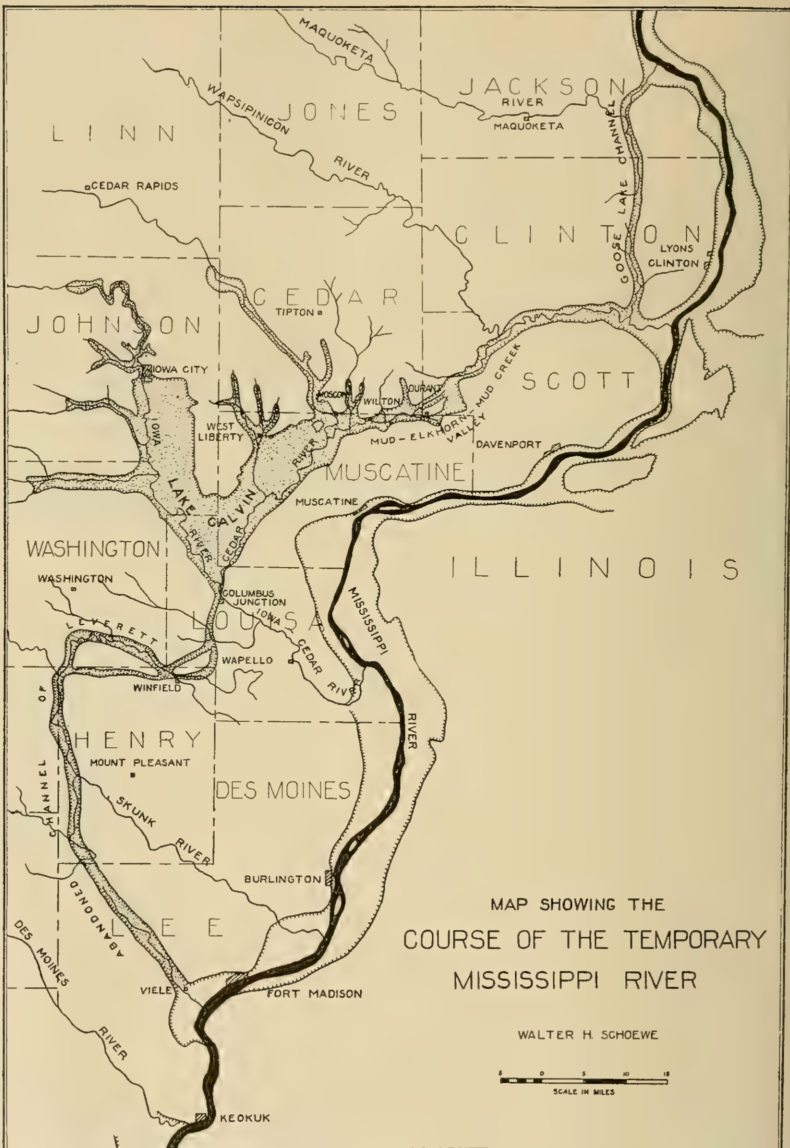
MAP SHOWING THE
COURSE OF THE TEMPORARY
MISSISSIPPI RIVER
WALTER H. SCHOEWE
SCALE IN MILES
LINN
JONES
JACKSON
CLINTON
CEDAR
JOHNSON
SCOTT
MUSCATINE
WASHINGTON
LOUISA
HENRY
DES MOINES
LEE
ILLINOIS
MAQUOKETA
WAPSIPINICON RIVER
MAQUOKETA RIVER
CEDAR RAPIDS
GOOSE LAKE CHANNEL
LYONS
CLINTON
TIPTON
IOWA CITY
LAKE CALVIN
WEST LIBERTY
MOSCOW
WILTON
DURANT
MUD CREEK
MUD - ELKHORN VALLEY
DAVENPORT
CEDAR RIVER
IOWA RIVER
MUSCATINE
WASHINGTON
COLUMBUS JUNCTION
LEVERETT
WAPELLO
WINFIELD
MOUNT PLEASANT
SKUNK RIVER
MISSISSIPPI RIVER
BURLINGTON
ABANDONED CHANNEL OF
DES MOINES RIVER
VIELE
FORT MADISON
KEOKUK

Fig. 1

rise from 25 to 40 feet above the flood-plain of Cedar River. Although the slope is not apparent to the eye, the terraces have a gentle inclination to the south. The surface of these terraces is approximately 660 feet above sea level at their northern extremity at West Liberty and Moscow, and from these points they slope gently to their southern extremities in Louisa County, 18 miles distant, where they have an elevation of 615 feet. Scattered over the entire area, but especially in the vicinity of Cedar River, there are low-lying sand mounds or dunes. On the west side of Cedar River, the terrace is remarkable for its uniform width, since out of the $22\frac{1}{2}$ miles of its total length, it maintains for a distance of 14 miles an average width of $4\frac{3}{4}$ miles. Here also, the terrace is continuous for its entire length, but, on the east side of the river, it is broken into nine remnants. Immediately west of Moscow, on the west bank of Cedar River, is an island-like highland which is a half mile distant from the main upland to the northwest, the surface of which rises, on the average, 75 feet above the level top of the surrounding terrace. This upland remnant has an area of about $1\frac{1}{2}$ square miles. The bluff line on the north and east is cut into the Devonian limestone and is therefore very well defined. Toward the south, and especially toward the southwest, the border of the remnant is less conspicuous, due to the presence of numerous sand dunes.

Exposures of the materials in the terraces are not numerous, because of the extreme youthfulness of the topography and the slight relief of the region. The surface materials consist of fine yellowish to brownish or drab-colored loess-like silt and sands, the latter forming the dune areas previously described. A few scattered bowlders dot the terrace surface. Most of the wells on the terrace are about 30 feet deep, but one at Nichols is recorded to have penetrated at least 250 feet[1] of unconsolidated material. The various outcrops, for the most part, show a fine- to medium-grained white to light-brownish sand, the strata of which in the northern part of the terrace are thin and essentially horizontal. Farther south, the sand shows cross-bedding and numerous thin layers of pebbles, the largest of which have a diameter of less than 1 inch.

[1] J. A. Udden, "Geology of Muscatine County," *op. cit.*, Vol. IX (1899), p. 355.

ABANDONED CHANNEL SOUTH OF COLUMBUS JUNCTION

The abandoned channel south of Columbus Junction was discovered by Leverett as early as 1896. This channel, which is outlined on Figure 1, has been described in detail by Leverett in his monograph on the Illinois glacial lobe.[1] The channel extends southward from Columbus Junction for a distance of 12 miles to the vicinity of Winfield. Separating into two branches at this point, its course continues westward to the valley of Skunk River at Coppock. Thence the temporary course of the Mississippi is southward for a distance of 18 miles to the bend of the Big Cedar, where it leads southeastward across Lee County to the valley of Mississippi River at Viele, 6 miles below Fort Madison.

This ancient valley of the Mississippi is incised below the general upland surface of the Kansan drift plain 30 to 60 feet. The valley floor rises 120 feet above the level of Iowa River at Columbus Junction, where it lies at an elevation of about 700 feet above sea level. Its general width ranges from $1\frac{1}{4}$ to $1\frac{1}{2}$ miles. The valley is well defined but is more conspicuous the farther southward it is traced. At the divide in Sections 35 and 36 of Elm Grove Township, Louisa County, 7 miles south of Columbus Junction, the valley floor is 1 mile wide and 35 to 40 feet below the general upland level. Several miles south of Columbus Junction bedrock appears in the valley walls and that part along Skunk River is cut largely in solid rock. It has been estimated that the excavation along the channel from Columbus Junction to Viele amounts to one-half a cubic mile.[2] Unusual deposits of sand and gravel are lacking in the channel.

VIEWS REGARDING THE DURATION OF THE TEMPORARY MISSISSIPPI RIVER

Concerning the general displacement of the Mississippi River by the Illinoian ice sheet, Leverett states that "with the recession of the Illinoian ice sheet the Mississippi shifted to its present course between Clinton and Fort Madison.[3] And in speaking particularly

[1] F. Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey, Monograph XXXVIII* (1899), pp. 91–93.

[2] F. Leverett, *op. cit.*, p. 93.

[3] F. Leverett, "Outline of Pleistocene History of Mississippi Valley," *Jour. of Geol.*, Vol. XXIX (1921), p. 622.

of the abandoned channel south of Columbus Junction, he states that

> The abandonment of the lower end of the channel from Columbus Junction southward probably cocurred as soon as the ice sheet had withdrawn sufficiently to uncover the present line of the stream, for the altitude along the present Mississippi bluffs is a few feet lower than the beds of the abandoned channel. This lower altitude along the Mississippi is due to the incomplete filling of the preglacial channel by drift.[1]

Concerning Goose Lake channel, he concludes that its occupancy "may have continued down to Wisconsin time."[2] Carman[3] is of the opinion that Goose Lake channel and Mud–Elkhorn–Mud Creek Valley were followed for only a short time after the retreat of the Illinoian ice sheet. Udden[4] also does not favor the view that the channel south of Columbus Junction was occupied for any considerable time, although he is of the opinion that Mississippi River did follow the Cedar River part of the temporary Mississippi River until the Iowan ice incursion. Udden believed that Cedar River Valley between Moscow and Columbus Junction had lost its river-like character and had taken on the form of a lake very similar to that of Lake Pepin in the Mississippi River at the mouth of the Chippewa River. To this wide expanse of water, Udden gave the name "Lake Calvin" in honor of its discoverer, Samuel Calvin.

Recent work by the writer on the origin and history of extinct Lake Calvin has convinced him that the former Mississippi River followed the westernmost course for a long period of time, perhaps to the time of the Iowan glaciation.

NEW FACTORS BEARING ON THE DURATION OF THE TEMPORARY MISSISSIPPI RIVER

The duration of the temporary Mississippi River involves two factors which up to the present time have received no consideration. They are (1) extinct Lake Calvin and (2) Illinoian gumbotil.

[1] F. Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey Monograph XXXVIII* (1899), pp. 96–97.

[2] F. Leverett, "Outline of Pleistocene History of Mississippi Valley," *Jour. of Geol.*, Vol. XXIX (1921), p. 622.

[3] J. Ernest Carman, "The Mississippi Valley between Savanna and Davenport," *Illinois Geol. Survey, Bull. 13* (1909), p. 62.

[4] J. A. Udden, "Geology of Muscatine County," *Iowa Geol. Survey*, Vol. IX (1899), p. 355.

EXTINCT LAKE CALVIN

Lake Calvin was formed at the time of the third or Illinoian ice invasion. The great ice sheet coming from the state of Illinois found its way westward, filled the valley of the Mississippi River, and advanced into the southeastern border counties of Iowa. In its advance, the mighty river had to abandon its course and was forced to find the new one described above. As the present course of Iowa-Cedar River was occupied by the great ice mass forming a dam across its valley at Columbus Junction, the combined waters of Mississippi, Maquoketa, Wapsipinicon, Cedar, and Iowa rivers and those flowing from the edge of the ice were ponded back, giving rise to the large lake labeled "Lake Calvin" on Figure 1. During the long existence of the lake, the surplus water found its way to the unfilled valley of the Mississippi below Fort Madison by way of the abandoned channel south of Columbus Junction.

The shape of the basin formerly occupied by Lake Calvin, considered in broad, general outline, is that of a huge letter V, made irregular by numerous ramifications, especially in the northern part of the lake site. The arms of the V extend in directions parallel to Iowa and Cedar rivers, and meet near the junction of the two streams at Columbus Junction, Louisa County.

Without including the numerous river-like irregularities north of Iowa City, West Liberty, and Moscow as part of the lake basin proper, the lengths of the Iowa and Cedar river arms of the V are 28 and 24 miles, respectively, with corresponding average widths of 4.4 and 5.8 miles. The widest portion of the old lake is $2\frac{1}{2}$ miles south of Lone Tree, where the bluff lines are separated by a low, flat stretch of country nearly 15 miles wide. At the time of their greatest expansion, the waters of the lake covered an area of approximately 325 square miles.

The site of former Lake Calvin, which is now an extensive lowland, has been described on pages 423 and 425. At least three sets of terraces occur in the lake basin, two of which represent the ancient floor of the lake. Laminated silts 35 feet thick characterize the lake terraces, whereas sand and gravel with typical fluvial cross-bedding and pocket-and-lens type of structure mark the third terrace.

Although known to Calvin[1] as early as 1874, partially mapped and described by Udden[2] in 1899, and noticed by Leverett[3] in the same year, conclusive evidence of the existence of Lake Calvin had not been presented until the writer[4] completed his studies on the origin and history of extinct Lake Calvin in 1919.

ILLINOIAN GUMBOTIL

So long as Lake Calvin existed, the Mississippi must have followed the temporary course outlined on the previous pages. Hence any evidence favoring a long life for the lake must favor at the same time a long duration for the temporary Mississippi River.

The duration of Lake Calvin is intimately related with the formation of the Illinoian gumbotil. For, as it will be shown, the lake could not have been drained until after the gumbotil was formed and the valleys of Iowa-Cedar and Mississippi rivers were developed. It has been shown by Kay[5] that in the formation of any gumbotil a very long period of weathering of the till is required and that during this period of weathering erosion is very slight. That the formation of the gumbotil is an exceedingly slow process is indicated by the fact that no gumbotil is found on the Iowan and Wisconsin drift sheets which are believed to be too young to have had a gumbotil developed on them.[6] The Illinoian gumbotil is on the average 5 feet thick.

During the very slow process of weathering of the till to form the Illinoian gumbotil, erosion was very slight. It is inconsistent with the theory of the formation and origin of the gumbotil that valleys sufficiently deep to drain the lake would have permitted the formation of the Illinoian gumbotil to the very edges of the valley walls. Especially is this true as the gumbotil lies in a horizontal plane and does not conform to the surface slopes produced

[1] J. A. Udden, *op. cit.*, pp. 352–53.

[2] *Op. cit.*, pp. 246–388.

[3] F. Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey Monograph XXXVIII* (1899), pp. 89–97.

[4] W. H. Schoewe, "The Origin and History of Extinct Lake Calvin, Iowa," *Iowa Geol. Survey*, Vol. XXIX, 1919. (In press.)

[5] G. F. Kay, and J. N. Pearce, "The Origin of Gumbotil," *Jour. of Geol.*, Vol. XXVIII (1920), pp. 89–125.

[6] *Op. cit.*, p. 124.

by erosion. From this one is forced to the conclusion that the gumbotil formerly extended across the valleys. It is conceivable, although there is no evidence for it, that Lake Calvin might have had an outlet across the Illinoian upland plain immediately after the ice withdrew without having involved much erosion and interfered with the formation of the gumbotil. That such could have been the case for any considerable length of time, however, is not probable. The level of the lake during its maximum height stood 120 feet above the present surface of the Iowa-Cedar River at Columbus Junction. The surface of the lake could not have been lowered appreciably without having resulted in pronounced erosion, which would have been fatal to the formation of the gumbotil. The presence of the lake, on the other hand, is fully in accord with the theory of the formation of the gumbotil, for the levels of the lake and of the gumbotil as they are shown at Columbus Junction are separated by not more than 10 feet, a difference in height which would hardly permit pronounced erosion.

The Illinoian gumbotil underlies the flat tabular stream divides and outcrops near the valley walls of Iowa-Cedar River and along both sides of the Mississippi, high above the present level of the rivers. This together with the fact that the gumbotil lies horizontally clearly shows that the present valleys of Iowa-Cedar and Mississippi rivers are incised below the general Illinoian upland plain and thus are post-Illinoian gumbotil in age. Therefore these valleys through which the lake was eventually drained could not have served as the outlet of Lake Calvin very soon after the ice had retreated. Thus Lake Calvin existed for a long time, and the displaced Mississippi must have followed the course south of Columbus Junction until the lake was finally drained by way of the Iowa-Cedar River Valley.

It appears that the earlier investigators based their conclusion of an early abandonment of the temporary course of Mississippi River south of Columbus Junction on three facts: (1) that there are no unusual deposits of sand and gravel in the now abandoned channel south of Columbus Junction; (2) that the elevation of the Illinoian upland bordering the present course of the Mississippi is only a few feet lower than the bed of the abandoned channel; and (3) that

the abandoned channel is not as well developed as Goose Lake channel.

It is commonly recognized that during the maximum advance of the Illinoian ice sheet the displaced Mississippi followed the course outlined in the preceding pages. On the assumption that a river occupied the valley of Iowa and Cedar rivers instead of Lake Calvin, the absence of the fluvial deposits can readily be accounted for by supposing that the stream has changed its course at Columbus Junction. On the other hand, if the filling up of the Iowa and Cedar River valleys is due to stream deposition, there appears no logical reason why deposits similar to those found north of Columbus Junction and in the Mud–Elkhorn–Mud Creek Valley should not be seen in the abandoned channel. There is no reason to believe that the streams were no longer overloaded when the waters used the channel, or that erosion has subsequently removed materials which may have been deposited there. The absence of such deposits demands explanation. A plausible and adequate explanation is offered by the supposed former existence of Lake Calvin. A lake acts as a filtering plant for a river, and accordingly it is easy to account for the absence of the fluvial deposits in the abandoned channel if Lake Calvin really existed and this channel served as its outlet. For comparison the streams emptying into and draining the Great Lakes may be cited. It is well known that many of the streams emptying into the Great Lakes are more or less discolored and muddy by reason of their load of sediment. Also it is true that such streams as the Niagara and the St. Lawrence which flow outward from the lakes are relatively free from sediment, and hence have little erosive power. Because of the settling of sediments in the lake basin and perhaps also because the ground in which the abandoned channel was excavated may have been frozen as suggested by Chamberlin,[1] it is not to be expected that the outflowing stream would have much erosive power nor much material to deposit. The absence of any considerable deposits of sand and gravel within the channel is then quite natural. This too may explain why this abandoned channel is not so well developed as the Mud-Elkhorn-Mud and Goose Lake channels.

[1] F. Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey Monograph XXXVIII* (1899), p. 93.

The fact that the Mississippi bluffs are a few feet lower than the bed of the abandoned channel does not preclude the drainage of the lake by way of the abandoned channel south of Columbus Junction. The Illinoian-Mississippian sag, if it really existed, was at least 20 miles distant from Lake Calvin by way of the present Iowa-Cedar River Valley. What the elevation of the intervening topography may have been is not known. The Illinoian upland at Columbus Junction is about 730 feet above sea level; at Morning Sun, only $2\frac{3}{4}$ miles from the south valley wall of Iowa-Cedar River, it is 752 feet; and at Newport, only 2 miles south of the river bluffs, it is at least 720 feet. The Mississippi bluffs north of Wapello are at many places over 700 feet above sea level. The Illinoian drift plain forms the upland surface on either side of the present course of the Mississippi, and Illinoian drift and gumbotil are exposed within several feet of the upper surface, high above the present level of the river. This clearly shows that the present valley of Mississippi River is incised below the general Illinoian upland plain and thus is post-Illinoian gumbotil in age. The same is true of the Iowa-Cedar River Valley.

On the basis of erosion alone it is not apparent why the Mississippi should have shifted its course to its present valley between Clinton and Fort Madison "with the recession of the Illinoian ice sheet."[1] All pre-Illinoian drainage lines must have been filled with drift, if not completely, at least partially, by the depositing Illinoian ice sheet. This is indicated by the presence of the gumbotil along the valley walls of the streams. According to Leverett, the altitude along the Mississippi bluffs is but a few feet lower than the bed of the abandoned channel which at Columbus Junction is 120 feet above the level of Iowa River. Hence an enormous amount of material must have been removed before the displaced Mississippi River could have returned to its former course. The process of removing this material must have involved a long time.

[1] F. Leverett, "Outline of Pleistocene History of Mississippi Valley," *Jour. of Geol.* Vol. XXIX (1921), p. 622.

REVIEWS

The Laramie Flora of the Denver Basin. By F. H. Knowlton. United States Geological Survey, Washington, *Professional Paper 130*, 1922. Pp. 175, pls. 27.

The Introduction deals with a history of Knowlton's investigations of the Laramie flora, which were begun in 1889. His original intention was to study the flora of the Laramie formation of the entire Rocky Mountains. The older collections, which had served as a basis for the work of Lesquereux, Newberry, and others, were to be critically reviewed, and the new material was to be added, but the unsettled condition of opinion regarding the Laramie group delayed the carrying out of this plan, and it was finally decided to restrict the study to an area about which there is little or no disagreement. Such is the Denver Basin in Colorado.

The paper deals with the plants known from the Laramie of the Denver Basin, the material being derived from many sources. While very considerable collections were brought together, Knowlton states that the flora is neither large nor very impressive, because the fossil plants of the Laramie are rarely found in great abundance. The matrix in which Laramie plants occur is usually a soft, friable sandstone which is not fitted to retain plant impressions with fidelity, and it is difficult to find perfect specimens. In attempting to present as complete a picture as possible of the plant life of the time, it has frequently been necessary to describe forms on rather slender data. But they are all figured and described adequately enough to be recognizable in the future.

Part I gives a historical review of the Laramie problem; Part II discusses the geologic relations and flora of the Laramie of the Denver Basin; and Part III deals with the Laramie flora itself. A complete list of the Laramie plants in the Denver Basin is given, together with various synonyms and changes of interpretation. The following genera are predominant in the flora:

Pteris	*Magnolia*
Sequoia	*Laurus*
Cycadeoidea	*Cinnamomum*
Juglans	*Platanus*

Hicoria	*Cercis*
Myrica	*Pistacia*
Salix	*Ilex*
Quercus	*Rhamnus*
Artocarpus	*Zizyphus*
Ficus	*Cornus*
Aristolochia	*Fraxinus*
Nelumbo	

Ferns were not very abundant as individuals, but diversified in type, and represented by eight genera and fourteen forms. The conifers appeared to have been an unimportant element. The only example belonging to the Cycadaceae is the beautifully preserved small trunk now referred to as Cycadeoidea. The monocotyledons were apparently not an abundant element during the Cretaceous period, and the Laramie flora is no exception. The dicotyledons were, of course, the most abundant and diversified elements of this flora.

Knowlton draws the following tentative conclusions as to the climatic conditions under which the Laramie flora may have existed. It seems to him beyond question that there must have been plenty of moisture on account of the abundant presence of coal and the apparent requirements of the majority of plants enumerated in his lists. It also appears to him a natural conclusion that the climate was warm, at least warm temperate.

Knowlton dwells at length upon the geologic relations of the flora, a feature which makes his paper particularly interesting for the geologist. He compares the Laramie flora with the Montana flora, Denver formation, Arapahoe formation, Lance formation, uppermost Cretaceous of the Atlantic Coastal Plain, Patoot Series of Greenland, and the Upper Cretaceous of Europe.

A. C. N.

Mineralogy of Pennsylvania. By Samuel G. Gordon. Special Publication No. 1, Academy of Natural Sciences, Philadelphia, 1922. Pp. 255, pl. 1, figs. 110.

Pennsylvania's mineral localities have been combed by generations of enthusiastic specimen hunters until there is scarcely a large collection anywhere in the world that does not include representatives from some of the famous localities of the state: Falls of French Creek, Wood's Chrome Mine, the Gap Nickel Mines, or the old lead mines of Phoenixville. The Pennsylvania Piedmont, with its great variety of rock types crowded into a small triangle in easy reach of Philadelphia, furnished a readily accessible collecting ground at the period when mineralogy was

experiencing its most rapid growth in this country. The classic localities have afforded type specimens that have woven themselves into the very fabric of the science.

The present volume sums up a wealth of published data and adds much original material gained through a decade of field and laboratory study. The book consists of two main divisions: the first takes up the mineral species in Dana's order with physical and chemical data and a list of localities for each species. While much information is repeated from standard mineralogies, the compactness and completeness of the data justify the duplication. All reliable and "semi-reliable" chemical analyses of Pennsylvania minerals have been included. Cuts from a variety of sources illustrate crystallography. In the second part of the book, the localities are described by counties and townships. A valuable feature of the book is the use of the Kemp co-ordinate system so that by a figure of four digits any spot may be located accurately on a topographic atlas sheet. The minerals under each locality are listed by paragenetic classes.

While considerable emphasis is placed upon paragenesis, economic geologists would probably have liked to see this phase given even more attention. The class "hydrothermal deposits," for example, is not subdivided, and veins of high and low temperature are grouped together. For some localities data are doubtless lacking, but for French Creek, Cornwall, and many other deposits, the author has sufficient first-hand acquaintance with conditions to have given his readers some interesting observations on mineral sequence.

An introductory chapter on "Origin and Occurrence of Minerals" gives a concise résumé of geologic processes. The statement (p. 4) that kaolin may be formed by hydrothermal metamorphism may be questioned. Tennantite is classed as an arsenide, although enargite is correctly described as a sulpharsenate. The growing number of believers in the hypogene origin of much bornite and some chalcocite would object to the omission of these minerals from the list of primary sulphides. Pyrrhotite is a serious omission from the list of primary iron minerals.

It is interesting to note that the author places rhodonite and tephroite among dynamic metamorphs (Iron Manganese Zinc Deposits) and not among contact or hydrothermal minerals, a viewpoint rather in accord with that of Palache,[1] who has made exhaustive studies of the minerals of Franklin, New Jersey, than with the recently published discussion by Ries and Bowen.[2]

[1] Unpublished discussion.

[2] "Zinc Ores of Sussex County, New Jersey," *Econ. Geol.*, Vol. 17, pp. 517–71.

Another chapter compiles in tabular form the salient features of the geology of Pennsylvania. The author considers the much discussed Wissahickon Gneiss as Ordovician in accordance with Rand[1] and not as pre-Cambrian as claimed by Bascom[2] and by Bliss and Jonas.[3]

A pleasing feature of the book is its exceptional freedom from typographical errors, particularly when it is considered that so many proper names have been used. A native of Chester County might offer the objection that Comley Hall was a man, not a building (p. 168: "field northwest of Comley Hall"), or a German might criticize the spelling: "regelmäfsig," but remarkably few mistakes of this sort are to be noted. The accuracy in the descriptions of localities will be best appreciated by those who have spent days in trying to locate some overgrown exposure from the vague information given by the older writers.

A fuller table of contents would have added to the convenience of the volume—the one used consists of only seven lines. The index, however, is adequate.

Not only will the work be indispensable to Eastern mineralogists and collectors but its mineral lists will prove of interest to economic geologists. A recent paper on the chalcocite of Bristol, Connecticut, has brought home the fact that much is to be learned from the old mines of the Eastern States. Pennsylvania localities, with their unusually complete lists of species and the elaborate suites of specimens available in many museums, offer attractive opportunities for paragenetic studies.

H. E. McKinstry

Casapalca, Peru

Physiography and Glaciology of Middle West Greenland. Abstract of part of results of Swiss Greenland Expedition. By Alfred de Quervain, P. L. Mercanton, and others. Ergebnisse der Schweizerischen Grönlandexpedition, 1912–1913. Denkschriften der Schweizerischen Naturforschenden Gesellschaft. Bd. 53. Zurich, 1920. Pp. 402, maps, diagr., photos.

The physiographic studies made along the front of the inland ice of Greenland in the vicinity of Jakobshavn by the Swiss expedition, are of exceptional interest as showing the conditions which may have obtained on the glacial fronts of America and Europe not many thousand years

[1] "Notes on the Geology of Southeastern Pennsylvania," *Proc. Acad. Nat. Sci., Phila.* XLIV (1892), pp. 174–202.

[2] Philadelphia Folio, 162, *U.S. Geol. Survey.*

[3] Prof. Paper 98-B, *U.S Geol. Survey*, 1916.

ago. Some of the striking features may be noted. The banding of the ice, apparently representing the annual layers, became steeper and steeper toward the edge, till it was nearly vertical near the frontal moraine. At many points in the lee of the frontal moraine there was such a collection of drifted snow blown off the ice-sheet that parasitic glaciers formed. The bare rocky zone beyond was deeply gouged and lake-filled. The difficulties of travel were increased by cryoconite, or the well-known dustwells, which pit the ice in some locations covering a quarter of the area. They occur in a zone within 10 km. of the west front of the ice. These dust wells consist of water-filled cylindrical tubes, mostly 5–10 cm. in diameter and 40–50 cm. deep, which contain earthy material on the bottoms. They have been formed by the melting induced by the extra heat absorbed by the dark covering of debris. The material has the fine-grained character of aeolian deposits, which appear to have been concentrated by flowing water on the surface.

The surface west of the ice-sheet was all glaciated except for an occasional high peak, above an altitude of 1,000 or 1,050 m. in the vicinity of Sermilikfiord, or above 1,300 m. far to the northeast. [On the sides of the east Greenland Sermilikfiord the continental glaciation extended up to 800 m.] The rugged peaks above the reach of the ice-sheet were in marked contrast to the rounded lower slopes eroded by the ice. In spite of active rock decomposition, the traces of glaciation were surprisingly fresh. Most striking were (*a*) the thinness and rarity of veneers of drift, (*b*) the intensity of the attack of the ice on the bed rock, and (*c*) the persistence of glacial polish. Erratics were in some cases well weathered, though resting on surfaces which were still smooth. The old striae were generally from the S.E., though the latest ones, from the thinner ice, crossed these generally from the east, the direction of the local slope. Both on the east and west coasts of Greenland large sections of rock have slid over the polished surfaces in front, making terraces with polished tops.

Evidences of local glaciers after the retreat of the main ice-sheet were found, especially in the south. Farther north the mountains were too low and the precipitation too small for such local glaciers to form. In the vicinity of Sermilikfiord (lat. 65° 30′—65° 40′) glaciers were found filling all the valleys. They were fed from extensive accumulators wherever the altitude exceeded 1,000 m. It seemed likely from Danish charts that this local ice extended northeastward all the way to the inland ice 100 km. away. These coastal glaciers were evidently not relics of the inland ice for, though the moraines were considerable, they did

not show signs of extensive retreat. In 1912, however, the glacial fronts seemed to be generally receding. Three glaciers of Blaesdal, Disco Island, were found to have retreated during the past fifteen years, continuing a preceding recession.

Marine terraces gave other evidence of local glaciation. In the vicinity of Kuk (lat. 66° 48′ N., long. 52° 17′ W.) and Sarfanguak, the lowest terrace was at 40 m. above sea-level, and was composed of a layer of till, covered with marine-laid sediments, another layer of till, and a top layer of mussel-bearing sand. Evidently, during the formation of these deposits, the land was depressed and the tongue of the valley glacier supplying the sediments retreated, advanced, and retreated again. The character of the fossils indicates a climate at that time too warm to have been associated with inland ice as far out as this.

The expedition was able to make some valuable observations of icebergs. Icebergs, even though tabular at the start, usually were so melted and exploded that they did not reach the open sea as large masses. Many bergs carry portions of sub-glacial caverns, which are visible in various stages of destruction. Calving takes place by hydrostatic lifting, or by falling or pushing off. As this occurs there is much exploding from the sudden release of the highly compressed air in the glacier. This air goes into the glacier with the original snow, and the increasing weight piled on top of it brings on enormous compression which, when suddenly released by calving, hurls a berg into a thousand pieces in successive explosions. In Disco Bay the sizes of icebergs ranged up to 75 m. high and 640 m. long.[1]

Charles F. Brooks

Earth Evolution and its Facial Expression. By William H. Hobbs: Pp. xvii+178, plates 6, figs. 84. New York: The Macmillan Co., 1921.

This volume of 178 pages is well printed on good paper, and is illustrated with many diagrams and sketches. Although it seems to be addressed to the general reader, it is rather too technical for any but trained students of the earth sciences.

In the opening chapters, the author outlines the progress of ideas regarding the state and origin of the earth, and concludes that Laplace's theory is now generally discredited, while that of Chamberlin "has the most general support among students of earth science." He also decides

[1] A discussion of the maintenance and ablation of the inland ice is included in a review published in the *Geographical Review*, July, 1923.

in favor of those who consider that the earth is made of nickel-iron enveloped in stony meteoritic material and kept in a rigid state by pressure.

The author is convinced that igneous magmas are the result of the fusion of shales and other sedimentary beds locally where occasional relief of pressure permits. Such relief is explained in two ways—the rising of a competent stratum in an anticline, and under uplifted fault-blocks. He argues that laccoliths are of this origin. Apparently batholiths are merely enlarged or coalesced laccoliths. He regards these domes as the initial stage in the forming of large anticlines and supposes that the Colorado-Montana region affords proof of the theory. To this end he is obliged to redate the pre-Cambrian granites of the anticlinal cores and put them in the late Cretaceous; but unfortunately the field facts are conclusively against him.

As to the mode of egress of magma thus formed, he agrees with Daly that blowpiping by gases and vapors which collect at the crown of the laccolith, is the chief process. These gases are not "juvenile" but are acquired from the shales fused and from rocks invaded during the ascent.

Turning to the general deformation of the earth, the author not only accepts the tetrahedral theory, of which the book gives a good summary, but he adds a novel modification of it, whereby the earth is supposed to have developed a twinning along a plane following the ancient Sea of Tethys. This left the hypothetical Paleozoic continents of Atlantis and Gondwana protruding to the north and south. Why this twinning did not affect the earth in earlier and modern times is not explained. The author ridicules those timid persons who suspect the existence of narrow land bridges from continent to continent in earlier periods in order to account for the strange distribution of faunas and floras past and present, and favors the bolder idea that the existing ocean basins have been made in large part by the collapse of the Permian continents, especially in the Atlantic and Indian regions.

The mountain arcs of southeastern Asia are interpreted as young anticlines—not overthrust from the land, as Suess presumed, but underthrust from the ocean basins. In this he seems not to have been aware of the earlier writings of Chamberlin and others regarding the sinking of the oceanic sectors resulting in the crowding of the continental borders. His argument is by no means convincing, and the experimental illustration fails because the photograph of the apparatus is not clear.

The forms of the arcs in plan are then discussed, but if there is in the chapter anything deserving to be called an explanation, the reviewer has

not found it. The position of the arc is said to be determined by the frontal slope of the mud lense built outward along the continental shelf. This soft yielding mass is apparently supposed to behave as the stiff rod, bent in the middle, which the author cites for comparison. The arcs are believed to have been formed in succession from the old coign outward.

The theory is said to explain the sequence of lavas, in such regions as the American Cordillera, from andesitic to rhyolitic and basaltic, and also the facts of distribution of lavas in comagmatic regions. The first fusion is supposed to affect the "average" shale and thus form an andesitic magma. Later the fusion spreads to layers of siliceous shale on the one hand and calcareous shale on the other, and from these are derived the constitutents that change the original magma to siliceous or basaltic composition. This is considered typical of the regions of active folding.

On the other hand the regions where the author believes faulting to be dominant, such as the Atlantic basin, are characterized by basaltic and alkaline lavas. The prevalence of these is explained by supposing that, in the process of faulting, a massive competent layer of limestone generally tends to separate from an underlying layer of calcareous shale. This, being relieved of pressure, liquifies and forms a basic magma.

In his concluding chapter, the author comments upon the tendency of most scientific men to sanctify certain theories, and their tardiness in recognizing the consequences of the passing of a discarded theory.

Like previous works by the same author, the book is interesting and suggestive, and it also reveals the same defects of loose reasoning, inaccurate understanding of field facts and earlier writers, and hasty conclusions.

Eliot Blackwelder

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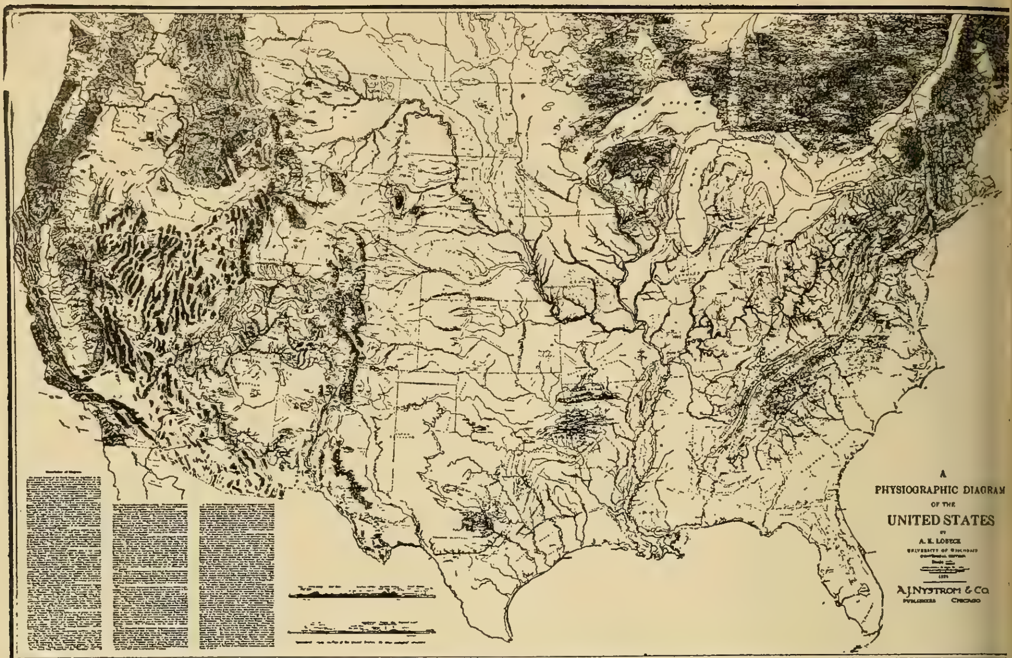
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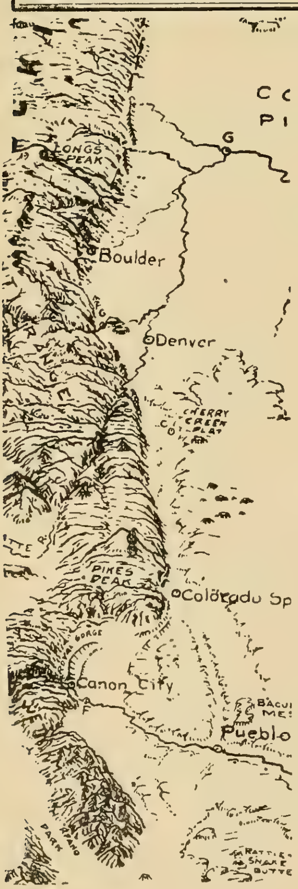
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THE JOURNAL OF GEOLOGY

September-October 1923

SUMMARY OF THE GEOLOGY OF THE BEARTOOTH MOUNTAINS, MONTANA[1]

ARTHUR BEVAN
University of Illinois, Urbana, Ill.

OUTLINE

[1] An abridgment of a thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy at the University of Chicago, 1921.

Presented in condensed form at the Chicago meeting of the Geological Society of America, December 1920.

LOCATION AND EXTENT OF THE RANGE

The Beartooth Mountains are in southern Montana and northwestern Wyoming, where they form the front range of the Rocky Mountains. The range has the approximate form of a broad, much elongated, slightly curved oval which extends southeasterly from Yellowstone Valley above Livingston to the canyon of the Clark Fork of Yellowstone River, about 30 miles northwest of Cody, Wyoming (Fig. 1). It is about 80 miles long and has a maximum width of about 30 miles south of its central portion, northeast of the northeast corner of Yellowstone Park.

The boundary between the range and the Great Plains is sharply marked (Figs. 2 and 3) but the boundary on the southwest is much less definite. South of the state line the Clark Fork is taken commonly as the line of demarcation between the Beartooth Mountains and the Absaroka Range to the west. In Montana the two ranges merge more or less, which makes it difficult to draw a sharp natural boundary between them. For this discussion the boundary is taken mainly along the divide between the streams that flow south and west to Yellowstone River and those that pursue a northerly course across the greater portion of the Beartooth Mountains to the same river far beyond the front of the range. Inasmuch as this boundary roughly follows the structural limits of the range, it is less arbitrarily chosen than may appear from this statement.

The range lies wholly within the drainage system of Yellowstone River. With the exception of Soda Butte Creek and a few other small creeks that flow into the northeastern part of Yellowstone Park, all of the streams flow northeasterly from the plains-ward front of the range across the bordering plains for many miles before uniting with the trunk stream. The main streams are permanent, even in seasons of excessive drought, as they receive an abundant and constant water supply from numerous perpetual snow fields, several small glaciers, and a multitude of lakes that are scattered throughout the range.

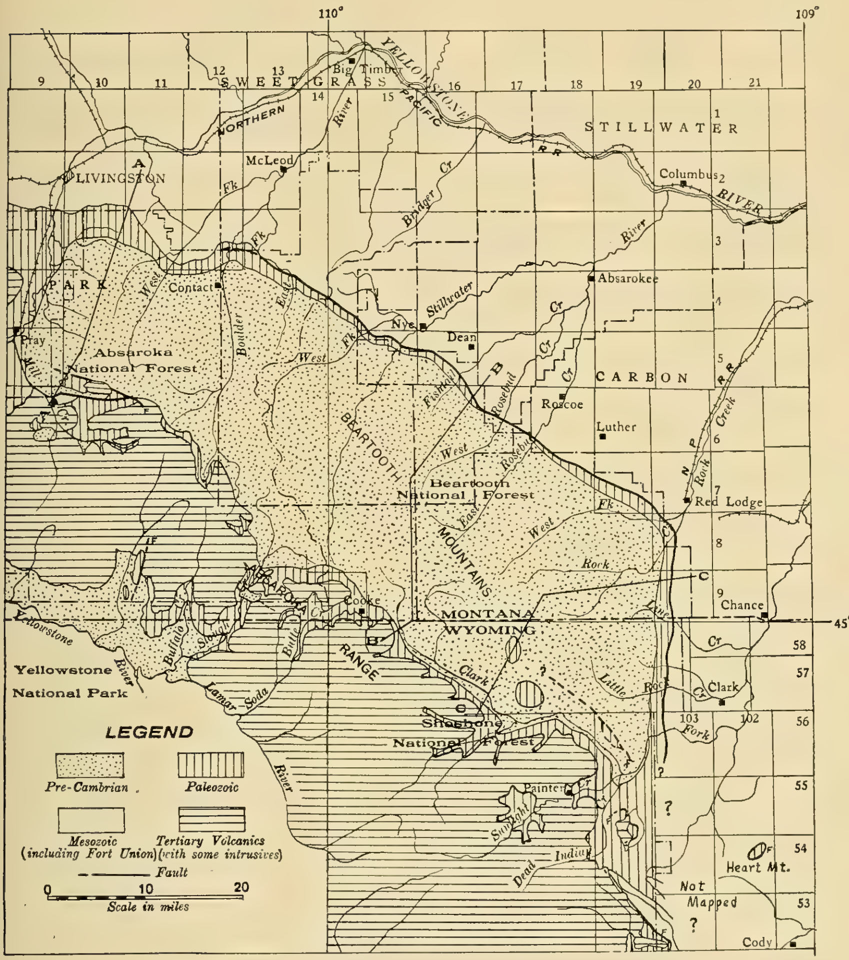

FIG. 1.—Sketch geologic map of the Beartooth Mountains and environs. Based in part on publications of the United States Geological Survey. Geology northwest of Cody after C. L. Dake. Geology west and south of Livingston somewhat generalized.

FIG. 2.—Topographic map of the central part of the Beartooth Range. Note the abrupt plains-ward front, extensive flattish areas of the sub-summit plateau, summit plateau remnants between 109°30′ and 109°40′, glaciated area on southwest slope, and the canyon-like valleys on the northeast slope.

SALIENT TOPOGRAPHIC FEATURES

The plains-ward front.—The Beartooth Range rises abruptly to a height of a few thousand feet above the Great Plains on the northeast. The 6,000-foot contour almost everywhere follows the base of the range, and the plains-ward crest has an elevation of 9,000 to 10,000 feet. In the southern part the frontal slope is uncommonly steep, but to the north it is neither so steep nor so uniform nor everywhere so sharply separated from the bordering plains.

The sub-summit plateau.—The remarkably even outline of the crest for considerable distances, especially in the southern half of the range, is an impressive feature (Fig. 3). It marks the plains-ward rim of a broad flattish plateau that extends along the eastern portion of the range for most of its length. This extensive surface is herewith designated, from its form and topographic position, the "sub-summit plateau." It consists of a series of gently undulating upland flats, each containing several square miles, that are the remnants of a once continuous erosional plain (Fig. 2). The largest tracts are about 10 miles wide and have an area of 10 to 20 square miles. Extensive portions of some of these plateau remnants are strikingly flat (Fig. 4).

In its longest dimension, parallel to the axis of the range, this plateau varies in altitude from slightly less than 10,000 feet, in the vicinity of Boulder River, to more than 11,000 feet in the central portion, then drops a few hundred feet toward its southern extremity. Its surface rises gradually toward the interior of the range, but becomes increasingly steep toward the main axial divide.

Sharp valleys 3,000 to 4,000 or more feet deep have been carved in this plateau by the several northeasterly flowing streams and their numerous tributaries. The dissection is least advanced in the southern half of the range and has progressed farthest in the northwestern portion, but even here the old surface is partially preserved in flattish tracts of considerable size. East Boulder and West Boulder plateaus, which are shown on the topographic map of the Livingston, Montana, quadrangle, are fairly typical remnants, but the best examples are in the south-central part of the range, just north of the Wyoming boundary (Figs. 2 and 4).

FIG. 3.—The plains-ward front of the Beartooth Range west of West Rosebud Creek. The elevation at the base is about 6,000 feet and at the summit about 10,000 feet. The even crest marks the rim of the sub-summit plateau, which is notched by cirques.

FIG. 4.—A portion of the sub-summit plateau showing its remarkable flatness over large areas. The altitude is about 10,000 feet. The rocks are pre-Cambrian crystallines. Silver Run Plateau, southwest of Red Lodge, in the foreground, with Line Creek Plateau to the south beyond Rock Creek.

The summit plateau.—The axial portion of the range is characterized by two distinctly opposing features: its extreme ruggedness, and the flattish summits of many of the dominant peaks (Fig. 5). The highest peaks and ridges of this rugged district in the south-central part of the range exhibit remarkably even-crested summits when viewed from any direction. The most extensive remnant of

Fig. 5.—Remnants of the summit peneplain along the main divide at the head of Rock Creek. Elevation of the even crests is about 12,400 feet. Looking southwest from Silver Run Plateau.

the summit plateau, which is called the Beartooth Plateau,[1] exists just north of the Wyoming boundary. It is a narrow, deeply notched plateau with an area of several square miles, which coincides with the axis of the range for about 12 miles (Fig. 2). Its rim almost everywhere overlooks very steep slopes or sheer precipices, most of which are from 1,000 to more than 1,500 feet high. The

[1] The name Beartooth Plateau has been used by some to mean the sub-summit plateau along the eastern front of the range, or the glaciated plateau on the south-western slope. The writer follows the usage of the term on the published topographic map of the Beartooth National Forest, where the name is restricted to the summit plateau.

elevation of this plateau is approximately 12,000 to 12,400 feet, or about 1,500 to 2,000 feet above the general surface of the sub-summit plateau. As observed from an altitude of 12,200 feet in the vicinity of Granite Peak it appears to have a southwesterly dip of about 5° (Fig. 6).

FIG. 6.—The summit peneplain southeast of East Rosebud Valley. The elevation is about 12,400 feet. The rocks are pre-Cambrian crystallines. Looking southeast from the vicinity of Granite Peak.

STRATIGRAPHY[1]

The pre-Cambrian core.—The main mass of the range consists chiefly of pre-Cambrian granite and granite-gneiss, with subordinate amounts of basic gneisses and schists. A considerable mass of anorthosite-gneiss exists on the east side of Boulder Valley, and extends southeast for an unknown distance.[2] Numerous basic intrusions, mainly dikes and small stocks, partly of pre-Cambrian age and in part possibly much younger, invade this crystalline core

[1] The areal geology of the northwestern portion of the range is shown by the Livingston, Montana, folio (No. 1), and that of the southwestern slope south of the state line on the Crandall sheet of the Absaroka, Wyoming, folio (No. 52).

[2] C. H. Clapp, oral communication.

in many places. Coarse pegmatite dikes are fairly common in the granite and gneiss. A unique feature is a large dike of pyroxenite that extends from Boulder River, below Contact, southeast beyond the head of Little Rocky Creek, southwest of Dean, and contains a large tabular deposit of high-grade chromite.[1]

No sedimentary formations of pre-Cambrian age have been discovered anywhere in this region.

Sedimentary formations.—Sedimentary formations are restricted to the flanks of the range. The indurated strata range in age from middle Cambrian to late Cretaceous or Paleocene. All the Paleozoic systems, except the Silurian which is absent, are represented by extensive deposits of limestone and dolomite with subordinate amounts of more or less calcareous shale and sandstone. The entire sequence is present along the eastern and northern base of the range, but erosion has removed most of the upper Paleozoics on the southwest slope north of the Wyoming boundary. Mesozoic formations are present only along the plains-ward front of the range and in the adjacent plains. All the systems are present. They consist preponderantly of alternating sandstone and shale with some limestone, gypsum, and coal. The upper part of the sequence in the northern part of the area is composed mainly of volcanic materials (Livingston formation). In Carbon County a thick series (Fort Union) of sandstone, shale, and coal lies with apparent conformity upon the youngest beds of undoubted Mesozoic age. Farther south along the mountain front a conspicuous conglomerate may be of later age.

The maximum thickness of the sedimentary formations on the east side of the Beartooth Range is approximately 18,000 feet. This is exclusive of the Livingston tuffaceous sandstones and agglomerates which in places are more than 5,000 feet thick. The Paleozoic systems have a total thickness between 3,500 and 4,000 feet, the undoubted Mesozoic systems about 6,000 feet, and the strata included in the Fort Union formation approximately 8,500 feet.[2]

[1] L. G. Westgate, "Deposits of Chromite in Stillwater and Sweetgrass Counties, Montana," *U.S. Geol. Survey Bull. 725–A*, 1921, pp. 67–84.

[2] E. G. Woodruff, "The Red Lodge Coal Field, Montana," *U.S. Geol. Survey Bull. 341*, 1908, Pt. II, p. 92.

The thickness of the individual formations and their main characteristics are shown in Table I. Many of the thickness values have

TABLE I

FORMATIONS IN THE BEARTOOTH MOUNTAINS AND ADJACENT GREAT PLAINS

Age	Formation	Approximate Thickness	Dominant Characteristics
		Feet	
Quaternary	....	?	Glacial drift, stream gravels, talus, and landslides
Tertiary	....	?	Andesitic breccias and lavas
Tertiary (?)	Fort Union (Lance (?) in lower part)	8,500	Yellowish sandstone and shale with several beds of workable coal; contains leaves and fresh-water shells
Tertiary (?) and Cretaceous	Livingston	3,000–5,000	Brownish and greenish andesitic sandstone and shale, with a thick member of andesitic agglomerate; lower beds are leaf-bearing
Cretaceous	Montana group: Bearpaw	125	Dark-gray clayey shale with scattered concretions and a few thin sandstones; marine invertebrate fossils
	Judith River	375	Soft, gray to yellowish sandstone and sandy shale with some lignitic beds; fresh- and brackish-water shells
	Claggett	435	Gray sandstone and sandy shale; marine and brackish-water invertebrates
	Eagle	200–300	Gray to white sandstone, thin- to massive-bedded, with sandy and carbonaceous shale; contains workable coal; marine fossils in lower part
	Colorado	2,000–3,700*	Dark-gray clayey shale with some intercalated sandstone and scattered calcareous concretions; marine fossils
Comanchean	Kootenai	300–500	Buff coarse-grained to conglomeratic sandstone, and purple to maroon shale
Comanchean and Jurassic (?)	Morrison	150	Dark-gray to greenish-gray sandstone and shale
Jurassic	Ellis	350–450	Greenish and reddish sandy shale, gray sandstone, and gray limestone; becomes sandy limestone to northwest; abundant marine fossils
Triassic	Chugwater	0–700	Red sandstone and shale with beds of gypsum
Permian (?)	Phosphoria	400	Gray quartzite and sandstone, chert, reddish shale, and impure limestone; marine fossils
Penn. and Miss.	Quadrant		
Mississippian	Madison	1,500	Light- to dark-gray, blue-gray and brown limestone in thin to thick beds; chert nodules locally; abundant marine fossils
Devonian	Threeforks	100	Dark-gray, thin-bedded limestone alternating with dark shale; marine fossils locally
	Jefferson	425	Light- to dark-gray and brown fetid dolomite; commonly thin-bedded; marine fossils locally
Ordovician	Bighorn	435	Light-gray to buff cliff-making dolomite alternating with thin beds; few marine fossils
Cambrian	Gallatin	400	Interbedded limestone and shale, flat-pebble conglomerate, glauconitic and oolitic beds; marine fossils, as trilobites
	Flathead	400	Shale, thin sandstone, and thin limestone; basal conglomerate locally
Pre-Cambrian (Archean?)	....	....	Mainly granite, granite-gneiss, and mica schist; basic gneiss locally

* This thickness is doubtfully assigned to the Colorado near Livingston by W. R. Calvert, *U.S. Geol. Survey Bull. 471*, 1912, p. 387.

been obtained from the publications to which reference is made in the footnotes.[1]

[1] The data for the Montana group in this area have been obtained largely from C. A. Fisher, "Southern Extension of the Kootenai and Montana Coal-Bearing Formations in Northern Montana," *Econ. Geol.*, III (1908), pp. 93–96.

The Flathead formation (middle Cambrian) and the Gallatin formation (middle and upper Cambrian) cannot be readily subdivided in this part of the state into the several formations that constitute the Cambrian system in the Little Belt Mountains[1] and northwest along the Rocky Mountain Front. The Bighorn dolomite apparently marks in this range the northern-most extent of the Ordovician in Montana. Although the formation is a lithologic unit with no evidence of a break in it yet discovered on the northeast side of the range, "a conspicuous surface of disconformity, with a basal breccia" exists in it on the extreme southwest slope.[2] It may be noted further that the Devonian of Montana apparently does not extend many miles south of the Beartooth Range in Wyoming. Hence this range contains one of the most complete Paleozoic sections in the northern Rocky Mountains. The Madison limestone is the bold cliff-making limestone (Fig. 7) which is so conspicuous throughout the northern Rockies. The Quadrant formation in the northern part of the range is roughly equivalent to the Amsden and Tensleep formations in Clark Fork Canyon at the southern end of the range. D. D. Condit has recently differentiated the Phosphoria formation in this region, and has indicated its distribution along the east base of the range.[3]

A narrow belt of the Chugwater "Red Beds," presumably in the main of Triassic age, is present along the base of the range in northwestern Wyoming, but disappears a short distance north of the state line. The Chugwater and Quadrant formations are overlain respectively by the Sundance formation in Wyoming and the Ellis formation in Montana—two marine formations that are equivalent in the main and of middle to late Jurassic age.[4] They are composed chiefly of interbedded shale and limestone in proportions which vary from place to place. Between the mountain front and Clark Fork River in the plains, the Morrison and Kootenai

[1] W. H. Weed, "Geology of the Little Belt Mountains, Montana," *U.S. Geol. Survey Ann. Rept. XX*, 1900, Pt. 3, pp. 284–87.

[2] C. W. Tomlinson, "The Middle Paleozoic Stratigraphy of the Central Rocky Mountain Region," *Jour. Geol.*, XXV (1917), 35.

[3] *U.S. Geol. Survey*, Prof. Paper 120–F, Pl. IX, 1918.

[4] Charles Schuchert, *Bull. Geol. Soc. Am.*, XXIX (1918), 246.

(or the roughly equivalent Cloverly) formations, both in the main of Comanchean age, the Colorado shale, and the divisions of the Montana group, are exposed in several places. The Morrison and Cloverly formations crop out only in the southeastern part of the district, where they consist of varicolored clastics and thin limestones of non-marine origin. The Kootenai formation is present

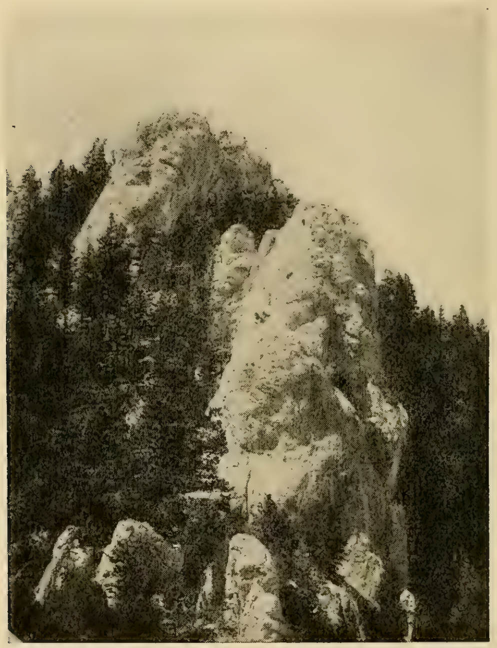

Fig. 7.—Massive Madison limestone that forms a conspicuous ridge west of Red Lodge. The beds are overturned slightly to the east (right). Gravel-capped Fort Union strata beyond east base of the ridge.

along the base of the range east of Livingston, where it corresponds approximately to the Dakota formation, as delineated on the Livingston areal map (Folio No. 1). The Colorado shale is the typical thick deposit of marine shale, but with more interbedded sandstone than is common farther north in Montana. A succession of non-marine sandstones and marine shales similar to that of the Lake Basin district[1] to the northeast, constitutes the Montana

[1] E. T. Hancock, "Geology and Oil and Gas Prospects of the Lake Basin Field, Montana," *U.S. Geol. Survey Bull. 691–D*, 1918, pp. 114–24.

group in Clark Fork Valley,[1] but the shales become distinctly more arenaceous and in part grade laterally into sandstone as the mountain front is approached. The Eagle formation contains workable coal in Clark Fork and Stillwater valleys.[2] Along the northern third of the range the Eagle is overlain by the thick tuffaceous beds of the Livingston formation, which apparently accumulated during the early Montana to Fort Union interval.[3] This formation consists of andesitic sandstones with a thick areally extensive lens of agglomerate as the middle portion.

The Lance formation has not been certainly identified in this region, and as typically developed on the Great Plains may be lacking. Detailed work in this part of the state will probably show that it is represented in the basal portion of the extraordinarily thick "Fort Union" section in Carbon County. Some of the tuffaceous sandstones in the upper part of the Livingston formation may be in part equivalent to the Lance.

The Fort Union formation occupies a broad area in the vicinity of Red Lodge and extends south along the mountain front toward the Wyoming line. It consists of a thick series of interbedded sandstone, shale, and clay, with numerous beds of coal in the middle portion. Several of these beds supply most of the coal produced in Carbon County. The entire formation is of continental origin.

Although the Fort Union formation in Montana is generally considered to be of early Eocene (Paleocene) age, there is a growing tendency to refer it with the Lance to the uppermost Cretaceous.[4] This is due in part to the apparent establishment of the Cretaceous age of the Lance by the discovery elsewhere of a member with a

[1] C. A. Fisher, *op. cit.*, pp. 77–99.

[2] Students of this region should note that the Laramie as shown on the Livingston areal map has been determined to be lower Montana, including the Eagle. See W. R. Calvert, *U.S. Geol. Survey Bull. 471*, 1912, pp. 386–89.

[3] R. W. Stone and W. R. Calvert, "Stratigraphic Relations of the Livingston Formation of Montana," *Econ. Geol.*, V (1910), 751–52.

[4] C. H. Clapp, "Cretaceous and Tertiary Continental Formations (of Central and Eastern Montana)," *Mont. Bur. of Mines and Metal. Bull. No. 4*, 1921, pp. 25–26.

W. D. Matthew, "Fossil Vertebrates and the Cretaceous-Tertiary Problem," *Am. Jour. Sci.*, 5th Ser., II (1921), 205–27.

Charles Schuchert, "Are the Lance and Fort Union Formations of Mesozoic Time?" *Science*, LIII (1921), 45–47.

marine Cretaceous fauna,[1] and the close relationship of the Lance and Fort Union formations. If the Lance is of Cretaceous age, the inclusion of the Fort Union in the Mesozoic is strongly supported by the lithologic similarity of the two formations, the homogeneity of the floras,[2] and the apparent lack of any pronounced hiatus in the Lance-Fort Union sequence. Moreover, upon the basis of recent studies of vertebrate remains in these and similar formations, the conclusion has been reached that the Fort Union belongs in the Cretaceous system.[3]

The Red Lodge district thus far has afforded no evidence bearing upon these phases of the problem. It is, however, a pertinent fact of considerable significance that the Fort Union of this region was involved in the first orogeny that deformed the underlying Mesozoic formations.

South of the Montana line within two miles of the mountain front is a line of hills formed of steeply tilted strata of a rather loosely cemented conglomerate which is composed mainly of well-rounded pebbles and cobbles of Paleozoic limestones. The age and relations of these beds have not been carefully determined, but from their position they seem to be either a part of the Fort Union or the marginal outcrops of the Wasatch of the Bighorn Basin. Although their lithology is more in accord with the published descriptions of the latter, their position and structure suggest that they may be a member of the Fort Union. They may possibly even be of intermediate age.

Another conglomerate, the Linley conglomerate, is present a short distance beyond the range, 10 miles northwest of Red Lodge, where it "lies with marked unconformity on tilted and eroded Fort Union beds."[4] It consists of about 300 feet (maximum) of sand and pebbles of igneous rocks from the crystalline core of the range,

[1] E. R. Lloyd and C. J. Hares, "The Cannonball Marine Member of the Lance Formation of North and South Dakota and Its Bearing on the Lance-Laramie Problem, *Jour. Geol.*, XXIII (1915), 253–57.

[2] F. H. Knowlton, "Are the Lance and Fort Union Formations of Mesozoic Time?" *Science*, LIII (1921), p. 307.

[3] W. D. Matthew, *op. cit.*

[4] W. R. Calvert, "Geology of the Upper Stillwater Basin, Stillwater and Carbon Counties, Montana," *U.S. Geol. Survey Bull. 641–G*, 1916, p. 203.

and a small amount of limestone. It is a local deposit, covering a few square miles, which is probably much younger than the conglomerate south of the state line.

Tertiary igneous rocks.—With the exception of the Livingston formation igneous materials of post-Cambrian age are not common in the Beartooth Mountains. Several dikes, sills, and stocks of Tertiary (?) age are present on the lower southwest slope in the Cooke mining district, and in the Haystack Peak area at the head of the main Boulder River.[1] On the east side of the range, south of Red Lodge, the Fort Union formation is invaded by a few narrow vertical dikes that are roughly parallel to the mountain front.[2] Some of the dikes and stocks within the pre-Cambrian core are probably of Tertiary age, but their extent remains to be determined.

The upper part of the imposing front of the adjacent Absaroka Range in northwestern Wyoming has been carved by the Clark Fork from more than 6,000 feet of volcanics that were ejected from the Crandall Basin volcano and associated vents during the Tertiary. The well-known landmarks of Pilot and Index peaks, which tower impressively above the southwest slope of the Beartooth Range, are sharply eroded from these formations. Although these volcanics do not now extend into the Beartooth Mountains, their great thickness and proximity indicate that their former eastward extent was much greater.

Terrace gravels.—Unconsolidated deposits of Tertiary and Quaternary age are widespread along the western margin of the Great Plains where they extend for many miles beyond the plainsward front of the Beartooth Mountains. The most common materials are stream gravels and bowlders of diverse constitution, which once probably formed an extensive piedmont plain. They have been worked over and over by the major streams and deposited in part at successively lower levels until now they mantle a series of broad terraces upon the truncated sedimentary formations along and between the principal valleys. Three or four of these terraces

[1] W. H. Emmons, "Geology of the Haystack Stock, Cowles, Park County, Montana," *Jour. Geol.*, XVI (1908), 193–229.

[2] N. H. Darton, "Coals of Carbon County, Montana," *U.S. Geol. Survey Bull. 316*, 1907, p. 186.

are commonly present, with the uppermost one several hundred feet above the present streams (Fig. 8).

Glacial drift.[1]—Glacial drift in the form of typical moraines and outwash gravels is present in most of the valleys on the east and northeast slopes of the range. This drift was deposited by fifteen systems of alpine glaciers, many of which contained numerous large tributaries. The outermost moraines commonly exist from 2 to 6 miles beyond the mountain front, but in a few valleys they are a

FIG. 8.—Terraces along West Fork of Rock Creek, southwest of Red Lodge

short distance within it. A few of the lateral moraines below the canyon mouths are huge ridges that attain heights of 500 to 1,000 feet above the valley floors (Fig. 9). Drift of two distinct epochs, probably corresponding to early and late Wisconsin, is clearly recognized in several valleys. An impressive characteristic of the recent drift is the abundance of large bowlders strewn over its surface. In some valleys the later glaciers advanced beyond the earlier ones, whereas in others the older lateral moraines extend a mile or two beyond the younger terminal moraines.

A considerable portion of the southwest slope was occupied by a large ice sheet which left an abundance of striated and polished

[1] A paper on the glaciation of the range is being prepared by the writer.

surfaces, countless perched bowlders, and extensive morainal deposits. The area thus glaciated is about 350 square miles between the base of the axial divide on the northeast and the front of the Absaroka Range on the southwest. An extraordinary feature of this glacier was the formation of several distinct valley lobes which passed into valleys sharply trenched athwart the axial divide, then descended these valleys to the plains beyond the eastern base of the range, where conspicuous moraines were formed.

Fig. 9.—The recent lateral moraine on the southeast side of East Rosebud Creek. Its height is about 600 feet.

STRUCTURE

General form of the range.—The Beartooth Range is structurally a broad asymmetric anticline that is in part strongly overturned toward the Great Plains and broken along its northeast limb by a huge fault (Fig. 10). The Paleozoic formations on the southwest slope commonly have low southwesterly dips whereas along the northeast flank they exhibit a variation from high easterly dips to overturned beds that are more than 70° beyond the vertical. Numerous minor faults and folds exist along this side of the range and in the adjacent plains.

The Beartooth overthrust.—The plains-ward front of the range is bounded throughout almost its entire length by the Beartooth

fault, which is an overthrust of considerable magnitude. West of Red Lodge the overturned Madison limestone on the west has been brought against the upper part of the Fort Union formation on the east side of the fault trace. Farther northwest, in the vicinity of West Rosebud Creek, the relations of the faulted formations are obscured by the widespread mantle of terrace gravel and glacial drift, but it appears that the pre-Cambrian crystallines abut

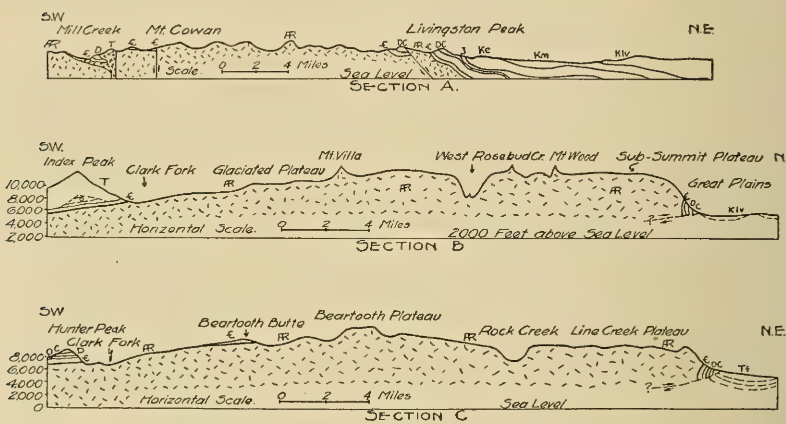

FIG. 10.—Geologic cross-sections of the Beartooth Mountains. Section A is a modification of section CDE of the Livingston folio. *AR*, Archean; *Є*, Cambrian and Ordovician; *D*, Devonian; *C*, Carboniferous; *J*, Jurassic and Comanchean; *Kc*, Colorado; *Km*, Montana; *Klv*, Livingston; *Tf*, Fort Union; *T*, Tertiary volcanics and intrusives.

against, or overlie, the upper part of the Livingston formation or the lower part of the Fort Union formation.

Along the southeastern front of the range, between the state line and Clark Fork Canyon, the Beartooth fault becomes a zone of thrust faults that in places cause the pre-Cambrian granite to rest upon the Chugwater "Red Beds" (Triassic).[1] "At one point the Chugwater is dipping west (overturned) at angles as low as 20°, and passes under the granite. At another point, the Dakota (Cloverly) was also seen dipping west at a very flat angle, and clearly upside down. The evidence of overturning rested not only

[1] C. L. Dake, "The Heart Mountain Overthrust and Associated Structures in Park County, Wyoming," *Jour. Geol.*, XXVI (1918), 52–53.

on the succession of beds, but on ripple-marks and cross-bedding, and is beyond dispute."[1]

The maximum thickness of the formations displaced by this fault is not less than 10,000 feet, and in places may be considerably more. The actual fault plane has nowhere been observed, but it dips westward at an angle apparently higher than is characteristic of most other Rocky Mountain overthrusts. The strata east of the fault are in some places sharply flexed whereas in others they

FIG. 11.—The Beartooth fault zone southeast of Stillwater Valley. Vertical Madison limestone along the range front, with gently east-dipping Livingston beds on valley slope. Looking southeast.

dip gently away from the fault zone (Fig. 11). At Red Lodge the Fort Union formation dips 18° toward the mountain front, but in the intervening distance of 4 miles it becomes horizontal, then dips gently in the opposite direction as the fault is approached.

The Beartooth overthrust appears to be the northward extension of the Heart Mountain overthrust of northwestern Wyoming, which has been determined recently by Hewett to have an eastward thrust of not less than 28 miles.[2] If not the direct continuation of the Heart Mountain fault it was very probably formed during the

[1] C. L. Dake, letter to the writer, Feb. 13, 1921.

[2] D. F. Hewett, "The Heart Mountain Overthrust, Wyoming," *Jour. Geol.*, XXVIII (1920), 536.

same orogenic epoch. Inasmuch as the fault plane is not exposed and remnants of overthrust beds, if ever present, have not been preserved beyond the eastern base of the range, the amount of horizontal displacement along the Beartooth front is indeterminable. In view of the enormous displacement at Heart Mountain beyond the southeastern end of this range, it is not improbable that the maximum displacement along the Beartooth fault plane was at least several miles, though this is not an absolute corollary.

Fig. 12.—The Clark Fork fault (?) along the southwest side of the range. Pre-Cambrian granite in the foreground, overlain by horizontal Cambrian in the distance. Range in background is of pre-Cambrian granite.

The Clark Fork fault (?).—The extreme southwest flank of the range, along the northeast side of Clark Fork Canyon, appears to be bounded by a considerable fault of the gravity (or "normal") type. A rapid reconnaissance trip in stormy weather permitted only a cursory inspection of the geology of this area, but the bold escarpment that here rises abruptly to the western rim of the sub-summit plateau is strongly suggestive of a fault. The topographic evidence is well shown on the topographic maps,[1] although no fault

[1] Crandall, Wyoming, quadrangle and the advance sheet of Part of the Shoshone National Forest, Wyoming.

is indicated on the areal map of the Crandall quadrangle (Folio 52). Furthermore, the pre-Cambrian granite of which the escarpment is composed rises abruptly more than 2,000 feet above Cambrian strata at its base, which are apparently horizontal, or at most only slightly warped (Fig. 12). This escarpment trends northwest and disappears southwest of Beartooth Butte in the crystalline rocks of the sub-summit plateau. The maximum vertical displacement of this fault may be several thousand feet, as all the Paleozoic formations, and an unknown thickness of the pre-Cambrian rocks, have been eroded from the summit of the range.

HISTORY OF THE RANGE

Antecedent conditions.—The Paleozoic and Mesozoic eras were a time of gradual preparation for the birth of this Rocky Mountain front range. An erosional plain of low relief that had been developed upon the pre-Cambrian crystallines was flooded by the middle Cambrian sea. Repeated incursions in subsequent Paleozoic periods resulted in the deposition of a considerable body of sediments upon the site of the future range. The general region was upwarped somewhat during the closing stages of the Paleozoic era but was peneplaned before the transgression of the middle Jurassic sea.[1] Throughout the remainder of the Mesozoic era a huge mass of marine and continental sediments, with a large body of intercalated effusives, accumulated over the area. The ejection of the volcanics appears to have been a premonitory symptom of the orogenic revolution which was soon to involve this region. That not remote portions of the province were already being affected by notable uplift and erosion is attested by pebbles of Carboniferous limestones and presumably pre-Cambrian granite in the Fort Union formation near Cody, Wyoming.[2]

Early Tertiary orogeny.—The climacteric event in the growth of the Beartooth Range was the profound orogeny which resulted in the huge overturned anticline and the great overthrust fault along its northeastern flank. The precise date of this epochal deforma-

[1] D. D. Condit, "Relations of Late Paleozoic and Early Mesozoic Formations of Southwestern Montana and Adjacent Parts of Wyoming," *U.S. Geol. Survey*, Prof. Paper 120–F, 1918.

[2] D. F. Hewett, "The Shoshone River Section, Wyoming," *U.S. Geol. Survey Bull. 541*, 1914, pp. 105–6.

tion is unknown, but the combined evidence afforded by the Beartooth and Absaroka ranges clearly indicates that it took place long after the deposition of the Fort Union in the former, and long prior to the accumulation of the widespread "early basic breccias" in the latter.

The folding of the Fort Union formation during the first orogeny that affected the underlying Mesozoic strata has been previously pointed out in this paper. If the Beartooth overthrust was essentially contemporaneous with the Heart Mountain overthrust, and at present there is no reason to doubt this, it occurred not earlier than the middle Eocene and may not have taken place before the early Oligocene.[1] This conclusion by Hewett as to the age of the Heart Mountain fault is based upon these facts: (1) the overthrust beds in places rest upon the Bridger formation (middle Eocene), and (2) the "early basic breccias" (upper Miocene) "locally lie in channels cut 200 to 300 feet below the overthrust surface."[2] It is significant that the overthrust mass is tentatively estimated to have been about 15,000 feet thick near the mountain front. In view of the complete removal of this thickness prior to the ejection of the upper Miocene volcanics it is hardly probable that the faulting took place later than the Oligocene.

Epochs of Peneplanation.[3]—Prolonged erosion initiated by this uplift reduced the ancestral Beartooth Mountains to the surface of low relief that is partially preserved in the flattish summits along the crest of the present range. The conclusion that these summit tracts are remnants of an ancient peneplain rests not alone upon the fact of their accordant levels, but is substantiated by their flattishness over a considerable area of diverse rocks in the central part of the range.

The age of this summit peneplain can not be closely determined with certainty on the basis of the available evidence, but its limits can be fairly well established. Inasmuch as the Beartooth over-

[1] D. F. Hewett, "The Heart Mountain Overthrust, Wyoming," *Jour. Geol.*, XXVIII (1920), 537.

[2] *Ibid.*, p. 555.

[3] For a more detailed discussion of this topic see a forthcoming article by the writer, "Rocky Mountain Peneplains Northeast of Yellowstone National Park."

thrust is post-middle Eocene, the peneplanation of the deformed mass most probably was not accomplished before the Oligocene, and perhaps not until the Miocene. Several lines of evidence, which are discussed in the forthcoming paper, point to the conclusion that this peneplain is not older than the Miocene, and may possibly be of Pliocene age.

After the completion of the summit peneplain the range was uplifted about 2,000 feet, with slight longitudinal warping and gentle tilting of the surface toward the southwest. This elevation seems to have resulted from renewed movement along the overthrust fault surface. The new cycle of erosion thus initiated continued until a large portion of the range was again reduced to an old age lowland—the present sub-summit plateau. The central part of the range remained above this extensive plain as unreduced remnants of the earlier erosion surface.

The age of this sub-summit peneplain can not be closely determined until the place of the summit peneplain in the erosional history of the range has been more accurately determined. It is evident, however, that this surface was produced in the erosion cycle which was begun by the deformation that elevated the earlier peneplain, and was closed by the uplift that resulted in the excavation of the present canyon-like valleys to depths of a few thousand feet. If the summit peneplain is as old as the middle Miocene it appears not improbable that the sub-summit peneplain is as young as the Pliocene, but if the former is of Pliocene age it is probable that the latter is of late Pliocene or early Quaternary age. Moreover, although the younger peneplain must considerably antedate the existing deep valleys, the fact that flattish remnants as large as 10 to 20 square miles in vulnerable positions have been but slightly dissected by tributary valleys strongly suggests that it may have been completed and elevated as recently as the Quarternary. The boldness of the mountain front, its abrupt rise for thousands of feet above the plains, and the slight amount of dissection over large areas support this view.

Quarternary events.—This second epoch of peneplanation was terminated by a vertical uplift of several thousand feet, which

enabled the streams to carve out the present system of sharp valleys. The movement was probably due to stresses that forced the overthrust mass still farther forward and upward along the fault surface. Warping of the uplifted peneplain appears to have been slight, as the difference in altitude may be due in part to the original slope of the plain. There is some suggestion in the stream profiles that the central part of the range was elevated more than the lateral or terminal portions. Westward tilting at this time is suggested by the fact that the valleys on the northeast side of the axial divide are cut much farther below the surface of the sub-summit plateau than are those on the southwest slope.

Another conspicuous result of the pronounced regional uplift has been the development of the bold plains-ward front of the range by differential erosion. The denudation of the highly resistant massive granite and gneiss has been comparatively slight since the uplift, whereas the much weaker Mesozoic and Tertiary (?) sedimentary formations of the adjoining plains have been worn to much lower levels.

Several subsequent broad elevatory movements of less vertical extent have successively rejuvenated the streams so that they have produced the series of terraces that exist along the principal valleys beyond the mountain front. The most recent important change of level seems to have preceded the earlier glacial epoch, for in East Rosebud Valley remnants of the right lateral moraine of this stage descend the streamward face of the first conspicuous terrace above the late glacial outwash.

The last noteworthy event in the history of the Beartooth Mountains was widespread glaciation during at least two distinct epochs. The glaciers on the northeast side of the summit divide were confined to the valleys whereas the plateau on the southwest slope was covered by the Beartooth ice-cap. Apparently the sub-summit plateau on the northeast slope has not been glaciated anywhere except at the heads of the valleys that rise within its borders, but it experienced considerable nivation. Meager remnants of the former extensive alpine glaciers still exist at the heads of several valleys on the northeast side of the main divide.

ACKNOWLEDGMENTS

The writer is greatly indebted to the late Dean R. D. Salisbury for suggestions in planning the investigation and for a conference in the field. Dr. C. W. Tomlinson first directed his attention to this region, and supplied manuscript sections of the Paleozoic formations on Dead Indian Creek and Livingston Peak. Professor C. L. Dake of the Missouri School of Mines kindly contributed certain information about that portion of the range in Wyoming. During part of the summer of 1916 Mr. A. S. Littick acted as field assistant and gave much aid in exploring the difficult portions of the range. Members of the United States Forest Service courteously assisted at every opportunity, but special credit is due Mr. A. M. Baum, then of the Beartooth National Forest. Material aid in furthering the work was freely given by Messrs. A. B. Cooley, A. H. Croonquist, and M. W. Potter, of Red Lodge, and Tom Phillips and F. W. Rich, of Dean.

WAS THERE PENNSYLVANIAN-PERMIAN GLACIATION IN THE ARBUCKLE AND WICHITA MOUNTAINS OF OKLAHOMA?

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INTRODUCTION

At intervals since August, 1920, the writer has been investigating the problem of glaciation, in Pennsylvanian and Permian times, of the Arbuckle and the Wichita Mountains, and on several occasions since December, 1920, brief reports of progress, illustrated with various photographs and specimens of the supposed glacial evidence, have been presented to scientific societies.[1]

It was intended to continue the investigation during the present summer (1923) but the Governor's veto of the appropriation for the Oklahoma Geological Survey, which supplied funds for the field work, temporarily at least, postpones the completion of the researches proposed. The following paper, therefore, though somewhat more complete than any heretofore presented, is only a preliminary statement of the data bearing on the question of Pennsylvanian-Permian glaciation.

Although the data accumulated and described are wholly the work of the writer, it is important to refer to the earlier work of two other geologists, namely, J. A. Taff in 1905 and W. H. Twenhofel in 1917, who have suggested the probable glacial origin of certain deposits in regions outlying some distance from, but nevertheless of the same general Carboniferous age as, the features herewith described in the Arbuckle and Wichita Mountain areas. Their work will be referred to more fully later as they give a certain measure of support to the interpretations expressed in this paper.

[1] "Evidence of Glaciation in the Arbuckle Region," read before Geological Society of America, December, 1921; see Abstract, *Bull. G.S.A.*, Vol. XXXII, p. 91. Read before Am. Assoc. Petrol. Geol., March 17, 1921. Read before Oklahoma Academy Science, February, 1921; see Abstract, *Okla. Acad. Sci.* Vol. II. (1922), pp. 73.

THE BOULDER CONGLOMERATES

While the distinctive evidence of the supposed glaciation is furnished by the occurrence of polished, striated, grooved and deeply fluted rock surfaces, nevertheless these particular erosion features were discovered only as the direct result of investigating the origin of certain non-residuary boulder conglomerates which are widespread in the region. These conglomerates form a series of distinct beds ranging throughout a large part of the Pennsylvanian and well up into the base of the Permian. Although the striated rock surfaces are found in association with only some of the latest boulder conglomerates, these conglomerates are all essentially the same in character, hence it is inferred that they have had a common origin under glacial conditions.

The boulder conglomerates of Pennsylvanian-Permian age in the Arbuckle Mountain region that are believed to have been formed either directly or indirectly by glacial action, include what has been termed the Franks Conglomerate.

The Franks Conglomerate at the type locality in the vicinity of Franks (see map, Fig. 1), on the northeastern slope of the Arbuckle region, consists of several distinct beds of conglomerate each 100 to 350 feet in thickness, interstratified with limestone, shale, and sandstone. The lowest conglomerate bed is about 150 feet in thickness and overlies the eroded edges of the pre-Pennsylvanian rocks of the locality. The beds at higher horizons occur as intra-formational conglomerates within the Pennsylvanian. At least as many as five distinct conglomerate beds may be distinguished at Franks, and at other localities on the north side of the Arbuckles. The Franks, therefore, consisting of a series of conglomerates rather than a single bed, it is convenient to refer to it for the present at least as the Franks series. On the south side of the Arbuckle Mountains several beds of conglomerate like the Franks have been recognized in the Pennsylvanian series, though they are not so thick as those on the north side.

In the Wichita Mountain region there are also thick conglomerate beds essentially of the same type as the Franks series in the Arbuckles. But the Wichita Mountain conglomerates have not been called Franks Conglomerate, for they have been usually considered of later origin than the Franks.

The Arbuckle and the Wichita areas are the remnants of ancient mountain ranges that were elevated during Carboniferous time. Their uplift began soon after the Mississippian and apparently continued throughout a large part of the Pennsylvanian and into the early Permian.

It is obvious that in the general degradation of the Arbuckle and the Wichita Mountain areas the agents of erosion would first attack the youngest rocks of the uplifted areas and then in succession each of the older formations in the reverse order of their deposition. The Paleozoic sedimentaries, beginning with the Mississippian, were

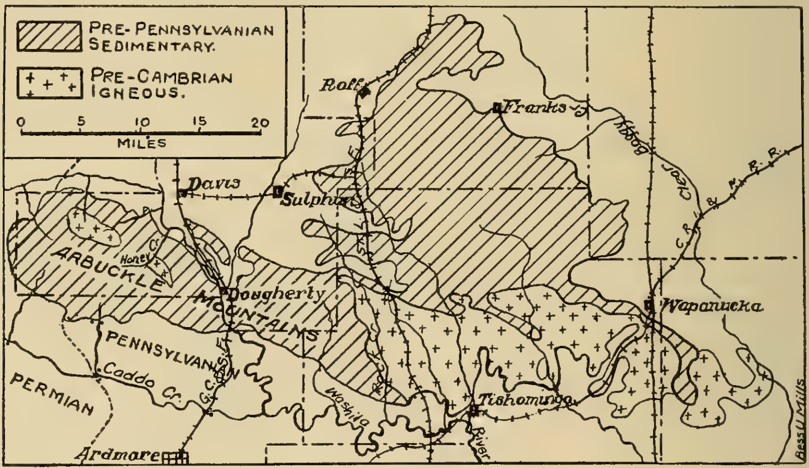

FIG. 1.—Sketch map of the Arbuckle Mountains

first removed before the underlying pre-Cambrian igneous rocks were exposed to erosion. In both areas, therefore, there are conglomerates of predominating Paleozoic limestone boulders formed in early Pennsylvanian times followed by conglomerates containing abundant pre-Cambrian igneous boulders of much later Pennsylvanian and Permian age.

In the Arbuckles, as now exposed, the conglomerates are largely of Paleozoic limestone boulders, and only some of the very latest conglomerates contain the boulders of the pre-Cambrian igneous rocks. On the other hand, in the Wichitas the pre-Cambrian igneous boulder conglomerates are the most abundant, and some of

the oldest of those now exposed as well as the youngest contain the pre-Cambrian boulders.

This difference in constituents of the conglomerates in the two areas is probably due to somewhat different conditions in the two areas which resulted in an earlier uncovering of the pre-Cambrian rocks in the Wichitas than in the Arbuckles. The earlier uncovering of the Wichita pre-Cambrian may have been due to a higher uplift of the Wichitas which resulted in faster erosion, or to a thinner covering of the Paleozoic, or to a combination of both of these conditions.

GLACIAL ORIGIN OF THE CONGLOMERATES

Whatever the correlation of these conglomerates it is their character and their probable origin to which attention is called. The glacial origin of the conglomerates is believed to be indicated by the following characteristics:

1. The heterogeneous character of the conglomerates, as indicated by the range in source of rock material and the great variation in size of the constituents in local deposits.

2. The non-residuary and unweathered character of the constituents of the conglomerate.

3. The great thickness of the conglomerate beds.

4. The occurrence of polished and striated surfaces of the rock floor upon which the conglomerate rests, and of polished, striated, and grooved pebbles and boulders in the conglomerate.

The phenomena described under the first three of these headings are of general occurrence and are everywhere exhibited by the conglomerate, while the features described under the fourth heading, which seem to indicate distinctive evidences of glaciation, are of more rare occurrence and are not everywhere developed or preserved.

In addition to the distinctive evidence of glacial origin furnished by the constituents of the conglomerate and the striated rock floors, there are on the flanks of the Arbuckle Mountains U-shaped valleys formed during the period of conglomerate deposition which possess the characteristic form of glacially eroded valleys. One of these U-shaped valleys, that of Honey Creek, has a polished and striated rock floor upon which the typical glacial conglomerate rests.

1. The heterogeneous character of the deposits is shown by a wide range in source, size and shape of the constituents of the conglomerate. Limestone is the most abundant boulder constituent in the Arbuckle area, as limestone is the most common rock of the Arbuckle region. In general, limestone pebbles from all the Arbuckle Mountain formations older than the particular conglomerates are brought together in each of the local deposits. In places there may be a predominance of boulders from adjacent or underlying formations, but very generally there is a complete mixture in varying proportions of rock débris derived from a wide range of formations. While there is a general tendency for coarse and fine beds of conglomerate to succeed one another, the individual beds show very little or no assortment. In the same bed the constituents will usually range from small pebbles up to boulders from 1 to 3 feet in diameter.

The shape of the pebbles and boulders also varies greatly, ranging from rounded to sub-angular and angular. In some deposits angular constituents predominate, in others rounded boulders are most abundant. Usually the more rounded and polished the boulders the greater the distance they have been transported. In some of the beds, at least, the most angular blocks have been derived from adjacent formations. However, any generalization meets with many exceptions, and well-rounded and very angular material from the various formations are often found together.

2. The non-residuary character of the pebbles and boulders is one of the most striking characteristics of the conglomerate. The constituents do not represent the end products of weathering, such as generally characterize basal conglomerates formed under ordinary sub-aerial or sub-aqueous conditions. On the other hand, the constituents are easily decomposable carbonate and silicate rocks which, judging from their angular shape and fresh, unweathered character, have been removed rather rapidly from their original source and transported considerable distances without much chemical decomposition.

It is well known that conglomerates or breccias formed of non-residuary material are characteristic of deposits on mountain slopes accumulated under desert conditions. The character of these

Pennsylvanian conglomerates, however, is such as to indicate their fairly constant association with water, as shown by the presence of many rounded water-worn pebbles and boulders, and their deposition in fairly distinct coarsely stratified beds. Furthermore, the Pennsylvanian conglomerates are not associated with any deposits suggestive of arid or desert conditions, such as the salt and gypsum deposits formed in later Permian time, but are on the other hand associated with coal seams and dark-colored carbonaceous shales indicating a relatively humid climate such as is required for abundant vegetation.

3. The great thickness of single conglomerate beds repeated at intervals in a series, is another striking feature. In the section at Franks there are at least five distinct conglomerate beds or formations, each ranging in thickness from 150 to 350 feet. In the section along Honey Creek, near Davis, the conglomerate is between 200 and 300 feet thick. There are other places where the thickness may reach as much as 1,000 feet or more. Such great thicknesses of conglomerate, it is believed, are rarely if ever formed upon the shores of ancient or present seas under ordinary conditions. On the other hand, such thicknesses of raw, unweathered débris are the common characteristics of conglomerates formed upon land, or in adjacent sea bottoms where glacial conditions exist, or have prevailed in the past.

4. In addition to the above-described characteristics which are usual features of glacial formations, there are the phenomena of striation and grooving which are believed to furnish the distinctive evidence of glacial action.

It may be thought by some that the striæ about to be described and illustrated by these specimens may have been formed by some other means than glaciation, such as by artificial means, or by such rock pressure movements as are developed along joint planes and fissures, in the manner of slickensided surfaces. There are, of course, various kinds of marks to be observed on rocks, both artificial and natural, and it seems hardly necessary to state that these various phenomena have been considered in the search for evidence of the glacial origin of these conglomerates. There are, for instance, numerous examples of polished and grooved surfaces developed

along joints and fissures in the closely folded and faulted pre-Pennsylvanian rocks of the Arbuckle region. Detached from their position along fissures some slickensided specimens might be taken for specimens showing glacial striæ, but no one observing such phenomena should have any difficulty in distinguishing glaciated surfaces from purely rock pressure surfaces in field exposures, because they are formed under quite different geological conditions, and are invariably to be observed under entirely different geological environments.

It should be stated in this connection that the most abundant striations and other evidences of supposed glaciation appear to be associated with one of the latest, if not the latest, conglomerate, deposited in both the Arbuckle and Wichita regions. This is especially true of the striations on the rock floor on which the latest conglomerate rests. However, some striated boulders and pebbles within the conglomerates have also been discovered in much earlier beds.

STRIATED ROCKS IN THE ARBUCKLE MOUNTAINS

The striæ thus far observed on the rock surfaces beneath the conglomerate in the Arbuckle region range from fine lines to fairly prominent grooves reaching an inch in width and one-fourth inch in depth. They usually run in nearly parallel directions and form distinct markings varying from a few inches to several feet in length.

The striated rock surface, shown in Figure 2 was found along the Santa Fé Railroad about 2½ miles north of Daugherty, where the underlying floor is exposed beneath a small projecting mass of the conglomerate. After two attempts by the writer to take a satisfactory photograph of this example in the field had failed, a fragment of the striated floor, (Fig. 2) was removed and photographed in a studio at Norman. The striæ at this place have a trend N. 25° E., as indicated by their position combined with the fact that the conglomerate overlying the striated floor contains abundant porphyry boulders and cobbles derived from porphyry outcrops (East Timbered Hill) which occur to the west. One of these porphyry cobbles which exhibits distinct grooving, and finer striations

FIG. 2.—Striated fragment of rock floor, $2\frac{1}{2}$ miles north of Dougherty

on the large groove, is shown in Figure 3. Other examples of striated boulders were found in the same locality.

Very fine striations are developed on the limestone floor of the conglomerate in the valley of Honey Creek about a mile below Turner Falls (see Fig. 4). The finely striated floor of the conglomerate is in the flat bottom of a distinctly U-shaped valley with relatively steep walls rising about 200 feet high. The smooth undulating rock floor covered with a few small patches of conglomerate is shown in Figure 5.

FIG. 3.—Grooved porphyry cobble in conglomerate overlying striated floor of Fig. 2.

The history of Honey Creek Valley and others like it on the flanks of the Arbuckle Mountains is complex, and deserves a special article in itself. The valley is U-shaped, especially below Turner Falls. It is mainly carved out of rocks of pre-Pennsylvanian age but in part also out of coarse boulder conglomerates of early or middle Pennsylvanian age, all of which have been folded to a variable degree and faulted. In the bottom of the U-shaped valley there is a formation of much later horizontally bedded conglomerate, made up of boulders of various sizes up to over a foot in diameter, which lies directly across the faults that affect the rocks of the valley walls. This undisturbed conglomerate, made up of boulders many of which are porphyry derived from points at least a mile or more away, can be traced out and grades into beds of finer sediments that surround the mountains and are considered to be at the top of the Pennsylvanian or in the basal portion of the Permian.

The smooth and striated floor of the valley lies beneath the horizontal conglomerate, and is exposed only where the present stream bed of Honey Creek happens to coincide with the old valley floor. The present stream develops a rough and jagged rock bed with-

out smooth and striated surfaces and it rapidly destroys and obliterates the smooth surface after removing the conglomerate. The striated surface is therefore found only beneath the conglomerate,

FIG. 4.—Striated fragment of floor of Conglomerate, Honey Creek valley

or where the conglomerate has been removed recently by the erosion of the present stream. Obviously the striated floor was formed under a set of erosion conditions quite unlike those now occurring in the valley. While the striations of the floor of the conglomerate are very fine (see Fig. 4), perhaps too fine to be especially distinctive

of a glacial origin, their occurrence in the bottom of a U-shaped valley and in direct contact with boulder conglomerates, both of which features are usually associated with glaciation, furnish a combination of geologic evidence strongly supporting the evidence of their glacial origin.

A striated limestone surface occurs along a branch of the Frisco Railroad about five miles east of Sulphur, where it was exposed by the removal of one to two feet of surface formation in constructing the railroad grade several years ago. This locality shows fairly

FIG. 5.—Polished smooth floor of Conglomerate, Honey Creek valley

prominent striæ and grooves, the more prominent of which are about three-fourths inch in width and about one-fourth inch in depth, some of them having a continuous length of about two feet over the smooth undulating limestone surface. The exposure is a gently sloping land surface of an upland area rather than a valley bottom.

The striated surface consists of the Arbuckle limestone, and is the floor of a late Pennsylvanian conglomerate that lies in patches in the vicinity, forming a continuous thick body a short distance to the west but thinning out to the east. The grooves have a trend nearly E.–W. and all are approximately parallel to one another.

There are some fresh irregular marks on the rocks apparently made by blunt iron tools during the process of excavating for the railroad grade, but these are quite unlike the grooves thought to be of glacial origin. The grooves thought to be of glacial origin are all essentially parallel in position, and many of the larger grooves show fine scratches superposed upon the grooves as though made by stony material having projecting sand grains.

Fig. 6.—Striated fragment, 5 miles east of Sulphur

No good photograph of the striated surfaces is available but in a recent visit to the place, there was found in the surface formation that overlies it, the fragment of limestone shown in Figure 6. This loose fragment is striated and grooved on two opposite sides and is apparently only a small portion of a larger flat piece of limestone that was subjected to abrasion when the overlying conglomerate formation was deposited.

GROOVED AND FLUTED GRANITES OF THE WICHITA MOUNTAINS

In the western part of the Wichita Mountains (see map, Fig. 7) there occur on the lower slopes of the mountains, numerous examples of polished, grooved, and fluted granite surfaces that have a marked resemblance to the work of ice erosion. Up to the present time the best examples have been seen southwest of Hobart, but not unlikely they may later be found to occur to some extent over the entire region. These grooved granites have been observed by other geologists who have visited the region, but they appear to have been referred to in the literature only by C. H. Taylor[1] who mentions

[1] "Granites of Oklahoma," *Okla. Geol. Survey, Bull. 20*, Plate XI, 1915.

the grooving incidentally in connection with a detailed description of the granites. It should be stated also, that the present writer has not yet seen all the examples of grooved granites reported to occur in the area.

The granite shown in the following illustrations is medium to coarse grained, of uniform granite texture, without any lines of

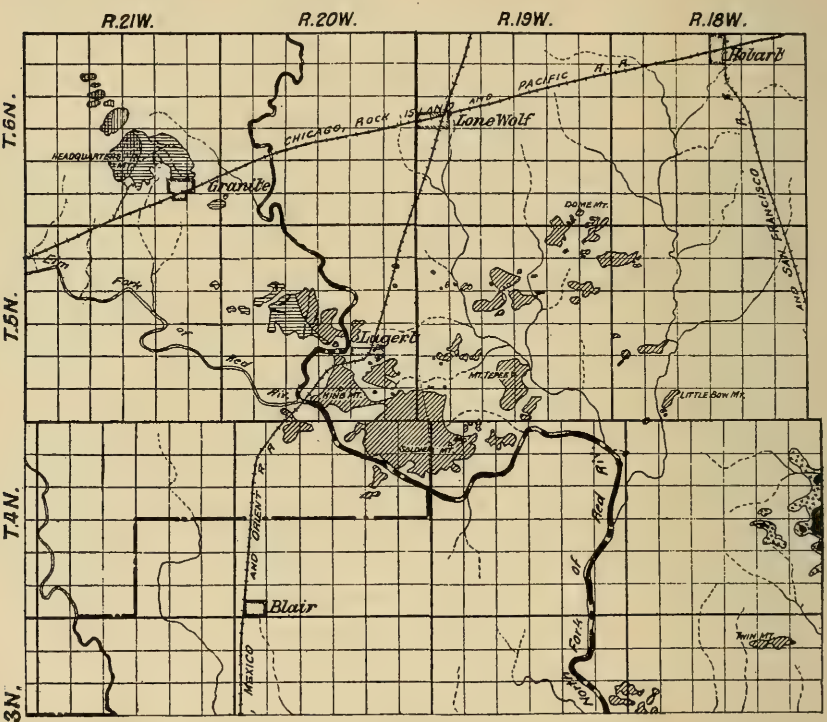

FIG. 7.—Sketch map of western part of Wichita Mountains. Shaded areas represent granite mountains, unshaded the plains of the Permian Red Beds.

structure or banding developed in it, excepting the numerous irregular joints and joint cracks that extend throughout. The grooves and flutings, therefore, depend in no way upon structural features of the granite formation.

The distribution of the grooved granites is limited to the lower slopes of the mountains about 100 feet above the lowest lands immediately adjacent. In their occurrence they are in close proximity

to coarse boulder deposits that occupy the lower slopes of the mountains. The boulder conglomerates are much eroded by the present surface drainage, and on the lower slopes they appear as remnants of a more continuous formation that once filled the intermontane valleys.

Above the general level of the zone of the grooved granites and the boulder conglomerates, the granite walls of the mountains rise to heights of 200 to 800 feet from the surrounding plains of the Permian Red Beds, and on these higher slopes are developed (see Fig. 16) the characteristic jagged or rounded exfoliation features, developed by granite under the stress of wind and weather.

FIG. 8.—View of grooved granite

The character of some of the grooved granite surfaces is shown in Figures 8, 9, and 10, which are examples occurring near the base of a granite mound that rises about 200 or 300 feet above the Permian Red Beds plain in the N.E. part of Sec. 7, T.5 N., R. 18 W.

Figure 8 shows deeply grooved granite near the base of the mound with the border of the plain sloping down to the right and with the top of the mound rising up on the left. The grooves are seen to extend around the outcurving heads of the projections and, though they disappear beneath the talus in the re-entrants in this particular place, they are believed to continue across as is indicated in Figure 11. The system of nearly, but not exactly, parallel grooves is approximately horizontal in this example. The grooved surface is roughened by spalling and other weathering processes, and the

middle projecting head has slumped appreciably from its original position.

A close view of another example of the grooved surface is fairly well illustrated in Figure 9, which shows grooves over one foot across and one-half foot deep. The ridges between the grooves show spalling and roughening by weathering. The sharpness of the grooves cut into the massive granite is illustrated in Figure 10, which shows a large block slumped down from the grooved zone adjacent. The grooved surface of Figure 10, because of its protected position on the under side of the turned-over-block, remains smoothly polished while the grooves shown in Figures 8 and 9, where unprotected and exposed to the sun, rain, and wind, are very rough.

Fig. 9.—View of grooved granite

The grooved granite surfaces are preserved to a variable extent on all sides of the mound, but the best examples, those shown in Figures 8, 9, and 10, are on the south side. In the re-entrant between two of the outcurving heads, partly covered by loose débris, a boulder was found fitting closely into one of the grooves. The side of the boulder next to the grooved surface was shaped to fit the groove as though it had been shoved along the groove by some semi-rigid body, such as ice, moving along the mountain side.

The continuity of the grooves and striæ about the outcurving heads and back into the re-entrants seems fairly well indicated in Figure 11. The grooved wall shown has a height of about 20 feet and as many as 50 or 60 distinct grooves and striæ are observable

on the largest face. While actual continuity of the striæ is broken in the farthest recess of the re-entrant where surface waters, after heavy rains from the slopes above, have concentrated and worn them away, there seems little reasonable doubt of their original continuity. The surface of the granite has been roughened by

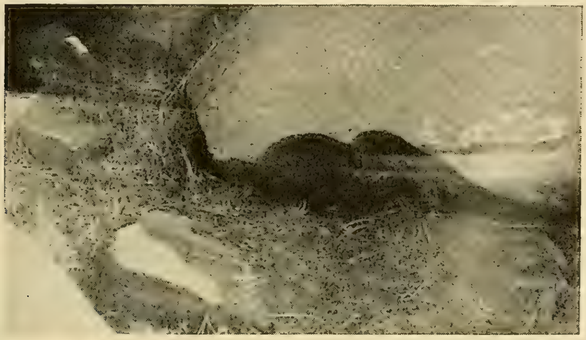

Fig. 10.—View of grooved granite, overturned block

Fig. 11.—View of grooved and striated granite

present weathering processes, but examples a short distance to the north show grooves with smooth and polished surfaces.

The manner in which the grooves and striæ entirely encircle small isolated stacks and bastions of granite is shown in Figures 12 and 13, which are views of the same rock taken from opposite sides. Although this particular example has been incidentally referred to

by Taylor[1] as a grooved boulder, it is the writer's interpretation that it is the top of a granite stack whose base is buried beneath the valley deposit. This interpretation finds visible support at least in the observations that no distinctly loose boulders of this type were seen in the area, and such grooved surfaces as these are known to entirely encircle some of the granite hills.

The grooved granite stands at the lower end of a valley on the south side of King Mountain, about two miles south of Lugert. The valley opens out to the south into the North Branch of the Red River. Figure 12 is a view of the granite stack with the east side

FIG. 12.—View showing grooves encircling granite stack. Seen from east side.

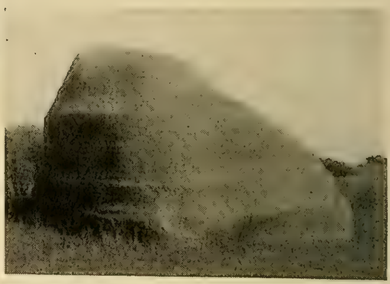

FIG. 13.—View showing grooves encircling granite stack, same as Fig. 12. Seen from west side.

of the mountain nearby in the background. On the left, at the same level as the grooved granite stack, the valley side shows some grooved surfaces, and on the slope higher up is a notch cut into the side of the mountain indicating what may be some faint traces of an ancient terrace. The opposite or west side of the grooved granite with the central part of the valley in the background is shown in Figure 13.

The grooved granite stack is elongated in a direction parallel with the valley, and its north end facing up the valley (to the right in Figure 12 and to the left in Figure 13) has a distinctly steeper and more abrupt face than its south end which faces down the valley. The end facing up the valley has the appearance of being undercut by the force of erosion that developed the encircling grooves, and

[1] C. H. Taylor, *Okla. Geol. Survey, Bull. 20,* Plate XI, p. 61.

this force was obviously directed by an agency which moved down the valley.

It may be assumed for the present that if glaciation was the cause of the extensive deposition of conglomerates, and of the various striated and grooved rocks just described, it was a type of valley glaciation developed on mountainous areas which probably stood as islands in the Pennsylvanian-Permian seas. There is no evidence from the conglomerates themselves to indicate anything other than their local origin, either within the Arbuckle Mountain area, or within the Wichita Mountain area. Perhaps in some places within the area between these mountains, there may have been a commingling of materials derived from the two mountain sources, but these places are now deeply buried by the later Pennsylvanian and Permian sediments. The present data therefore indicate that the glacial source was in the mountains adjacent to where the boulder conglomerates and the striated and grooved rocks are found.

Under this hypothesis the glaciers having their sources in the mountains descended the valleys and coalesced on the low lands, or in the seas that surrounded the mountainous islands. The present valleys occupy the lines of ancient drainage, and ancient valley glaciers, in moving down the valleys, would be in a position to develop such features as the grooved granite of Figures 12 and 13, which closely resemble the features of "crag and tail" of glacial origin. In the phenomena of "crag and tail"[1] isolated stacks and bastions of rock which faced the direction of ice flow are rounded and beveled off and frequently a hollow is dug out in front, while débris has been heaped up behind to form the so-called "tail" of the hill.

In the valley which contains the grooved granite stack are coarse boulder deposits in contact with the grooved granites which indicate some adequate means for the transportation of coarse débris from farther up the valley. In Devil's Canyon Valley, which lies adjacent to the east, there are grooved granite walls at various places along the valley which appear to indicate a marked descent of the grooves down the valley. While there is some rather steeply inclined grooving of the granite in this region (see Fig. 14), the grooves and flutings are in general approximately horizontal. Furthermore

[1] J. Geikie, *Earth Sculpture*, p. 242.

some of the valleys that lie on the flanks of the Wichita Mountains like that of Honey Creek in the Arbuckle Mountains, appear to have the distinctly U-shaped form which is typical of glaciated valleys. A probable example of a U-shaped valley in the eastern part of the Wichita Mountains appears to be that of the gorge of Canyon Creek, in Sec. 2, T. 4 N., R. 13 W.

The suggestion has been made that the grooved granites owe their origin to wave action of some sort. Indeed, in so far as explanations of these features have been offered, some form of water wave work has usually been suggested. The writer, however, can find no reference in literature to features of this sort made by water waves.

FIG. 14.—View showing inclined grooving

On the other hand the grooved and fluted granites bear a marked resemblance to the work of ice erosion, such as the rock scorings of various kinds described by T. C. Chamberlin[1] from the Pleistocene glaciation.

If the grooved granites are relics of ancient glaciation, the question naturally arises as to what has protected them from Permo-Carboniferous times to the present. As already stated the fluted surfaces appear only on the lower slopes of the mountains in a zone now occupied by the remnants of a coarse boulder conglomerate of Permo-Carboniferous age that once filled the intermontane valleys. The grooved granites are seen only where recent removal of the conglomerate by stream erosion has exposed them to view.

[1] T. C. Chamberlin, "Rock Scorings of the Great Ice Invasions," *U.S. Geol. Survey, 7th Annual Report*, 1886, pp. 155–248.

In Figure 15 is shown an example of recent uncovering of a fluted granite mass. This view shows in the foreground a small area of fluted granite standing on a low flat which has been exposed by stream erosion. In the background is seen a bank rising above the flat, which is the general level of the surrounding plain of the Permian Red Beds. The Red Beds once extended over the intervening low flat and completely covered the granite mass, but stream erosion has recently removed the Red Beds down to the intervening low flat, thus bringing to view the buried granite with its fluted surfaces. In addition to the work of streams ordinary slope

FIG. 15.—View showing recent uncovering of grooved granite

wash on the sides of the mountains, has exposed the grooved surfaces as in such examples as Figures 8 and 11.

An additional line of evidence in support of the view that the fluted granite surfaces are ancient features, brought to the surface by the removal of the valley fill, is the very obvious fact that these features are now in process of obliteration and destruction wherever exposed to present weathering conditions.

The present type of wind and weather action is fairly well illustrated in Figure 16, which represents an exposure at the head of Devil's Canyon and well above the zone of valley fill and grooved granite surfaces. This granite mass is an isolated stack, exposed

to the rigid action of wind and weather, resulting, as usual under such conditions, in the opening up of deep cracks along the penetrating joints and the weathering out of large blocks which become more or less rounded by exfoliation. There is no indication in this example, or anywhere else in the region, that the present type of weathering tends to produce the fluted granite surfaces. On the other hand the present type of weathering tends to destroy the grooved surfaces. Figures 8, 9, 10, and 11 show the fluted granites in various stages of destruction. Note how the surfaces of the flutings are roughened and the projecting ridges between the grooves

FIG. 16.—View showing features of the granite under present conditions of wind and weather.

broken off by spalling. Some of the outcurving heads are in process of slumping down the mountain slope and some lie completely dislodged and turned over.

Originally the fluted surfaces were smooth and highly polished as shown by the fact that in the most protected places the flutings are still smooth and polished. Some of the fluted granites are so markedly polished that they have served as favorable places for the pre-Kiowan Indians to carve their picture writings, obviously for the same reason that our granite workers select only the polished surface of monuments upon which to trace their finest lines of engraving.

The boulder conglomerates associated with the granite mountains in the western part of the Wichitas are largely granite material without appreciable amounts of calcareous cementing constituents and hence in most places are an unconsolidated formation. But where limestone material is abundant in the conglomerate, it is usually a firm consolidated formation. The unconsolidated character of much of the conglomerate composed of igneous rock boulders, sand, and clay has led to the suggestion that it may be of a later age than the Permian Red Beds. However, there seems no good reason to doubt the usually accepted correlation stated by Taff[1] that the boulder conglomerates at the base of the mountains are of the same age as the red shales and sandstones into which they appear to grade in the surrounding "Red Beds" plains.

WORK OF OTHERS

While the data bearing on the problem of Pennsylvanian-Permian glaciation here presented are wholly the work of the writer, it is important to refer to the earlier work of two other geologists who have either ascribed directly or at least suggested the possible glacial origin of certain Permo-Carboniferous deposits within the general region, but outlying some distance from the Arbuckle and Wichita mountain areas.

J. A. Taff, in 1905[2] and in 1909,[3] described the occurrence of erratic boulders in shales of Middle Carboniferous age in the Ouachita Mountains of eastern Oklahoma. The erratic boulders consist of various types of rock such as limestone, sandstone and quartzite, some of which are angular and ranging in size up to 50 feet in diameter. It was Taff's belief that the erratic boulders were ice-borne and derived either from the Arbuckle uplift or from associated areas farther to the south in Texas.

Taff seems not to have discovered any distinctive evidence of glacial striæ on the boulders described by him, and in 1912, J. B. Woodworth,[4] after making some investigations, reached the con-

[1] J. A. Taff, *U.S. Geol. Survey*, Professional Paper 31, p. 76.

[2] *Science*, Vol. II (1905), p. 225.

[3] *Bull. Geol. Soc. Am.*, Vol. XX (1909), p. 701; and *Science*, Vol. XXIX (1909), p. 637.

[4] J. B. Woodworth, *Bull. Geol. Soc. Am.*, Vol. XXIII (1912), pp. 457–62.

clusion that certain chert boulders mentioned by Taff in folded Carboniferous shales near Talihina, Oklahoma, had been shaped by earth movements and not by glacial action. The writer has seen these chert fragments in the folded and faulted shale at Talihina where they reveal abundant evidence of earth movements and agrees fully with Woodward's interpretation of their origin. It should also be stated that Taff fully recognized that certain marks on boulders described by him resembled slickensided surfaces.

There are, nevertheless, certain formations of Carboniferous age in the Ouachita Mountains of eastern Oklahoma containing a mixture of various kinds of large boulders derived from different sources, the origin of which as stated by Taff is difficult to explain, except in some manner through the agency of ice, probably the work of icebergs. If the evidence presented by the writer in the Arbuckle and the Wichita mountain areas indicates Carboniferous glaciation, the erratic boulders described by Taff would seem to fall naturally into the same category.

W. H. Twenhofel[1] in 1917 in a paper entitled "Granite Boulders (?) in the Pennsylvanian Strata of Kansas," described numerous large boulders, mainly of granite porphyry within the area occupied by formations of Pennsylvanian age near Rose, Woodson County, Kansas. Many of the boulders are as much as four feet in diameter, the largest being seven feet in diameter, and they appear to be unlike the granite boulders of the Pleistocene drift, the southern limit of which lies about 75 miles to the north. The boulders are now exposed on Pennsylvanian strata and while their correlation could not be fully determined, Twenhofel is inclined, for various reasons, to consider that they are of Pennsylvanian rather than of Tertiary or Pleistocene age, and that the boulders reached their present position through the agency of ice, either glacial or floating, more probably the latter. The possibility that the Rose boulders may be correlated with the Squantum tillite near Boston, Massachusetts, described by Sayles[2] is suggested by Twenhofel.

There are, therefore, in the rocks of Carboniferous age, some distance from but within the general region of the Arbuckle and the

[1] *Am. Jour. of Science*, Vol. XLIII (1917), pp. 363–80.

[2] *Bull. Mus. Comp. Zoöl.*, Vol. LVI, No. 2, Geol. Series, Vol. X (1914), pp. 141–75.

Wichita Mountains, as well as in more distant localities, as Massachusetts, certain deposits, the origin of which is much more reasonably ascribed to glaciation than to any other agency. It is, of course, now generally accepted by geologists that extensive glacial deposits were formed on all of the continents, except North America, during Carboniferous times. This fact, however, should not be given undue weight in support of the view that particular glacial-like deposits are necessarily of glacial origin because they were formed in the Permo-Carboniferous times. The character of the deposits and associated features themselves should furnish reasonable evidence of their glacial origin, if such is their origin.

However, marked changes in climate are known to be world wide in their effects and it would seem highly probable that if Permo-Carboniferous glaciation did so powerfully affect the other continents, such as Asia,[1] Australia,[2] Africa,[3] and South America[4] in particular, it should almost certainly have affected North America over considerable areas. If this were the case, such regions as the Arbuckle Mountains and the Wichita Mountains, which stood as high land areas during this period of general glaciation, would have been so situated that glaciation might reasonably be expected to have developed there.

[1] For an account of Paleozoic glacial phenomena, see C. D. White, "Carboniferous Glaciation in the Southern and Eastern Hemispheres," *Am. Geol.*, Vol. XIII (1889), pp. 299–332.

[2] W. E. David, *Q.J.G.S.*, Vol. LII (1896), pp. 289–301.

[3] Broom, *Geology of Cape Colony.*

[4] I. C. White, *Geol. Soc. Am.*, Vol. IX, pp. 512–21.

SOME EXPERIMENTS IN FOLDING

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University of Chicago

In 1812 Sir James Hall, using some pieces of cloth and a door "which happened to be off its hinges" and a few stones to act as weights, reproduced the contortions of the strata shown by the Berwickshire coast. This suggestion was revolutionary, for folding of strata had not previously been recognized.[1] Since that beginning, experimentation in folding has been carried on by many different investigators, among whom may be mentioned Favre, Daubrée, Pfaff, Forscheimer, Schardt, Reade, Cadell, Willis, Avebury, Paulcke, Königsberger, and Mead. No attempt will be made here to discuss in detail the results of these researches.

For many of the present experiments the pressure apparatus utilized was the crushing box previously used for experiments in faulting which have already been described.[2] Pressure can be applied simultaneously from both ends, if desired. As one side of the box can be removed at will, the progress of the folding can be observed and photographed at any stage of the deformative process. A comparison of the progressive changes and characteristics of the folds during the different stages of compression constituted an important part of the investigation. In most of the tests sand was placed both above and below the layers to be folded. This gave an adaptive support below, and effected a well-distributed weighting above. Heavy blocks of stone were placed upon the sand to afford sufficient overburden.

After testing various materials, mixtures of paraffin and vaseline were found to yield the most satisfactory results, and were employed in different proportions, depending upon the degree of competency desired. Pure paraffin was found to be too brittle for pronounced

[1] J. S. Flett, "Pres. Address, Sec. C," *Repl. British Assoc. Adv. Sci.*, 1921, p. 73.

[2] R. T. Chamberlin and W. Z. Miller, "Low Angle Faulting," *Jour. of Geol.*, Vol. XXVI (1918), p. 11.

folding, and is far better adapted to experiments on faulting. On the other hand, a layer of pure vaseline between stronger layers is extremely incompetent. The competency of experimental materials can thus readily be regulated by varying the relative proportions of the softening and hardening constituents. In some cases a small amount of plaster of Paris was added to develop the most competent layers. In preparing the succession of strata each layer was molded separately in a wooden frame having a paper bottom. With the materials used the layers were sufficiently plastic to weld together in a firm block of strata which was then placed in the compression box.

Criticism has sometimes been leveled at compression-box experiments, but the opinion may perhaps be ventured that observation of the stages of deformation of three-dimensional blocks gives one a much clearer conception of the processes of folding than can be obtained by a study of field sections. In addition there were many interesting and unexpected developments which arose independently of the main purpose of the investigation.

Mead has suggested that pressure-box experiments do not make accurate reproductions of folding as it occurs in nature, because they do not take into account the shrinkage of the earth beneath the mountain zone.[1] In Mead's very neat and effective experiments a tightened rubber band with a paraffin coating was allowed to shrink and thus deform the paraffin. This method would seem to rest on the assumption that the sub-crustal portion beneath the mountain range is shortening by compacting as much as is the mountain range by folding, but one may perhaps urge the alternative hypothesis that the shortening by compacting of the sub-crustal zone is more widely distributed under plain and mountain range, while in the crustal portion the shortening tends to be concentrated in the mountain ranges. On this hypothesis the compressive movements which produce the folding are not only the product of the compacting beneath the ranges, but also to a greater degree the product of the accumulated movement of the non-mountainous parts of the crust toward the growing mountains. The very common location of mountain ranges parallel or concentric with conti-

[1] Warren J. Mead, "Notes on the Mechanics of Geologic Structures," *Jour. of Geol.*, Vol. XXVIII (1920), p. 507.

nental borders and coast lines, seems to be an expression of directed horizontal thrusts which are only in part the result of earth shrinkage immediately beneath the mountains. Thus the pressure-box method, with its tangential forces, though not taking into account forces developed by compacting directly beneath the deformed strip, still possesses some advantageous features not possessed by the shrinking rubber-band method.

The present paper will discuss the bearing of some of the experimental results on geological theories.

ARCUATE TREND LINES

The remarkable arcuate chains of Asia and southern Europe have given rise to considerable geologic speculation. Suess assumed that in the case of Asia these arcs were produced by thrusting directed from the interior of the continent outward and toward the concave sides of the arcs.[1] In harmony with this, is the most commonly held view that, in general, the thrusting which has produced arcuate ranges has been directed against the inner or concave sides of the curves.[2] Hobbs, on the other hand, believes that in the formation of arcuate mountains, the active thrusting has been directed against the outer or convex side.[3] This belief was derived in the first place from theoretical considerations substantiated in his opinion by an experiment. In this experiment compressive stress was applied on two sides of what was essentially an equilateral triangle while the apparatus itself offered resistance on the third side.[4] The resulting folds naturally tended to form approximately normal to the compression which, in this case, produced an arc whose outer side faced the compression—the result sought. But one may readily suspect that if the thrusting could be made to act in just the opposite direction—from within the triangle outward against the steel sides

[1] Eduard Suess, *The Face of the Earth*, Sollas Trans., Vol. I, Part II.

[2] H. A. Brouwer, "On the Crustal Movements in the Region of the Curving Rows of Islands in the Eastern Part of the East Indian Archipelago," *Konig. Akad. Wetenschappen Amsterdam*, Vol. XXII (1916), Fig. 1, p. 775. O. Wilckens, *Allgemeine Gebirgskunde* (Jena, 1919), pp. 49–60.

[3] W. H. Hobbs, "Mechanics of Formation of Arcuate Mountains," *Jour. of Geol.*, Vol. XXII (1914), pp. 71–90; 166–88; 193–208.

[4] *Ibid.*, Fig. 8, p. 89.

of the frame—it would produce wrinkles with essentially the same trends. The above experiment did not appear to the present writers to decide the question. It seemed desirable to try experiments of a somewhat different sort.

Experimental results.—A rectangular model of much greater area than is possible in the pressure box was placed in position with side supports and an appropriate overburden. It was arranged so that pressure could be applied over a limited portion of the free side, either by a single steel jackscrew, or by two jacks operating inde-

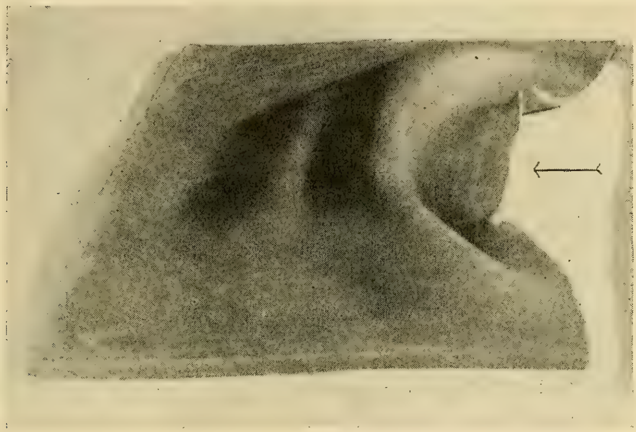


FIG. 1.—Arcuate fold produced by jack-screw in the position shown by arrow. The inner side of the arc faces the thrust.

pendently on different portions of the free side. By applying pressure over only a short strip of the model very good arcs were developed. The lines of force apparently radiate outward from the locus of active thrusting. The wrinkles then form more or less normal to the lines of greatest compression, developing curves whose concave sides face the thrusting. Thus it is found that arcs can be developed readily enough from compressive stress directed outward from a place within the inner curve of the ensuing arc (Fig. 1).

In the formation of many mountain ranges the intensity of thrusting has presumably varied from place to place, as suggested by the fact that the ranges are not entirely continuous. Places of greatest thrusting and greatest horizontal shifting of material would

present some analogies to the loci of applied thrust in the experiments just described. In such places arcs might develop with their inner curves toward the active force (Fig. 2). As a general rule, it is probably also true that the effects of the thrusting have presumably been somewhat greater in the middle portion of each range and have died off toward the extremities. Short mountain chains, in which the horizontal movement is considerable in proportion to the length, might perhaps develop curving trend lines because of this fact.

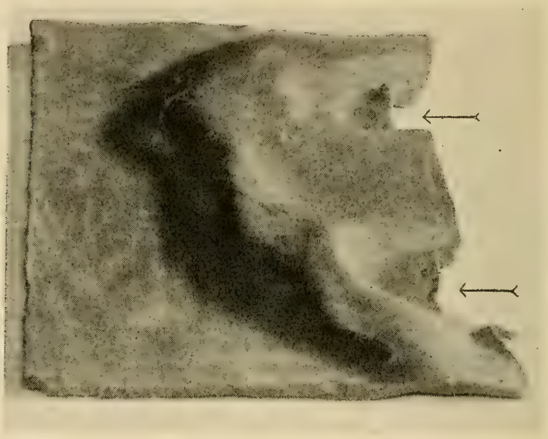


FIG. 2.—Force applied by two jacks (arrows) produced these arcuate folds. Their concave sides face the loci of applied thrust.

To test another possibility, a model was prepared in which a semicircular rigid plaster mass was incorporated in the usual relatively plastic mixture of paraffin and vaseline as shown in Figure 3. This would represent a rounded central mass of resistant old rocks, flanked by a zone of less consolidated sediments, after the analogy of Asia. The resistant plaster arc was placed on the side of the model farthest from the pressure which was applied uniformly by means of two steel jacks. It was suspected that the curvature of the resisting buffer might control, or at least greatly influence, the trend of the resulting fold. The result of the experiment was that while the fold manifested a slight tendency to conform to the curving outline of the resisting mass where the fold came closest to it, still the

tendency was not very marked. In general the trend of the fold did not conform to the shape of the rigid arc.

This would suggest that the curving mountain chains flanking the more rigid Tibetan mass do not, in the main, owe their concentric trend directly to the outline of the resisting mass. More likely in most cases it would seem that the belts of heavy sedimentation in geosynclinal tracts bordering the periphery of an elevated land mass, which also should have a slight curvature, may be the real factors which have determined the curving chains subsequently developed. A more or less circular or rounded land mass should naturally yield heavy sedimentation along its borders. Because of the relative weakness of these zones of sediments, and because of other factors

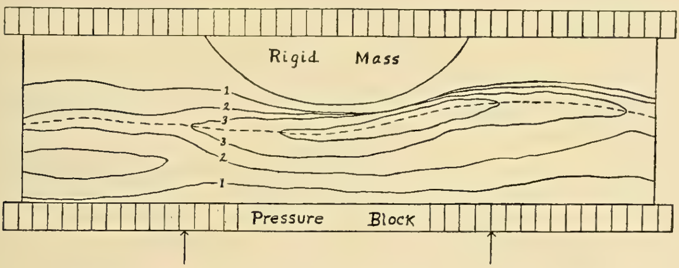


FIG. 3.—Result of deforming model between pressure board and rigid plaster mass. Folds contoured. Dash line indicates crest of principal anticline.

which cannot be discussed here, folding into mountain ranges subsequently appears in these marginal belts. Then, in the long geologic history the destruction of one range furnishes the material close at hand in more or less concentric belts, for the elevation of the next chain in some subsequent orogenic outburst. These successive generations of mountain chains follow a sort of cycle. The details of trend in a given range thus may be foreshadowed in part long in advance, and constitute an inheritance from a long sequence of ancestral conditions.

The problem of arcuate folding was studied from another angle. Inflated toy balloons were coated with paraffin by immersion in the hot liquid. After the paraffin had cooled somewhat, but was still quite plastic, the air in the balloon was allowed to escape slowly, causing the surface of the balloon to shrink. The paraffin, con-

forming to this shrinking surface, necessarily was folded or faulted. In many cases the axes of these folds were curved; in some places they formed arcs as intricate as the mountain ranges in the East Indies and southeast Asia. They suggest that arcuate folding may be the characteristic way in which a globe is deformed by internal shrinkage.

It would seem probable, therefore, from these various experiments, that mountain arcs are produced in several ways. A natural tendency of a globe undergoing deformation to yield along curved rather than straight lines is apparently a basal factor in the development of such ranges. This factor would operate, either by producing curving geosynclines through a long chain of ancestral conditions, or in some cases more immediately by developing curving folds directly. Such arcs would have their curvature already outlined in the early stages of the deformation. In addition, if the active force is from one side, or more from one side than the other, a progressive bending of the trend lines may occur as folding progresses, due to the holding back of the extremities while, with the maximum thrust in the center, that portion moves forward in a horizontal shearing movement, forming an arc which is concave toward the active pressure.

OVERFOLDS AND UNDERFOLDS

In Suess' explanation of the arcuate mountain zones of Asia and the festooned islands off the Asiatic coast, the active thrusting was supposed to come from the inner side of the arcs. Hobbs, however, approaching the problem from a different point of view, made the cardinal principle of his explanation active pressure from the outside of each arc. His criticism of Suess was based on his belief that there must be an actual stretching of the strata inside the arc to make possible the outward migration of materials to form the arc. Such an explanation, he believes, must require a noteworthy thinning of the strata in the upper limbs of the overturned folds.[1] If, on the other hand, the active force be directed from without, he believes that the under limbs of the folds (in this case underfolds)

[1] W. H. Hobbs, *Earth Evolution and its Facial Expression*, Macmillan and Co., 1921, pp. 124–26.

should be thinned. As folds with drawn-out upper limbs are not commonly found, Hobbs was led to conclude that the arcuate chains have been developed as underthrusts from without. In an earlier paper he attempted to show that underfolding is easier and more natural than overfolding.[1] To quote: "The active force (thrust) which produces rock folds, instead of operating from behind and above the anticline, as so generally supposed, is applied below and in front. Continuation of the process yields therefore not overturned and overthrust, but underturned and underthrust flexures." Willis, however, contends that overthrusting and underthrusting are determined by local conditions, among which the relative vertical positions of the active pressure and the passive resistance are most influential. If the line of pressure is directed above the resistance, the result is overthrusting. If the pressure be directed below the resistance, underthrusting results.[2]

Experimental results.—In many different experiments on folding in the course of these studies, it was found that either overfolds or underfolds may develop, though not with equal readiness. Apparently some local peculiarities, if of the right sort, may determine which way the fold will turn. These may be in the nature of slight differences in material, unevenness in the thickness of the layers, or a slight initial dip, which in the preparation of the layers is not always easy to eliminate. Variable resistance from the sand on the sides of the blocks of strata, or variability in the overburden, may also be influencing factors. But in a large number of trials such fortuitous variables should tend to eliminate themselves according to the law of averages, and the relative number of overfolds and underfolds should decide which is the more normal type. In these tests overfolds formed in much greater numbers than underfolds. Figure 4 (p. 498) shows the preference for overfolding.

It was found that the nature of the folding can be controlled to a certain extent according to the principle stated by Willis. The layers to be folded were attached to the movable blocks in such a way as to slope upward from the pressure block to the resistance block.

[1] W. H. Hobbs, "Mechanics of the Formation of Arcuate Mountains," *Jour. of Geol.*, Vol. XXII (1914), pp. 166–81.

[2] Bailey Willis, *Bull. of Geol. Soc. of Am.*, Vol. XXXII (1921), p. 31.

The pressure was thus applied at the lower edge of the gently inclined strata and consequently at a level somewhat below the resulting fold. This arrangement seemingly should favor the development of underfolds. In some cases it did, but in two experiments where an underfold began to develop, an overthrust formed on the steeper limb before the folding became very sharp, and this quickly became the dominant structure with further compression. This order of events seemed very significant, suggesting a strong tendency to overthrust rather than underthrust whenever the opportunity allows. In two other experiments where everything was arranged

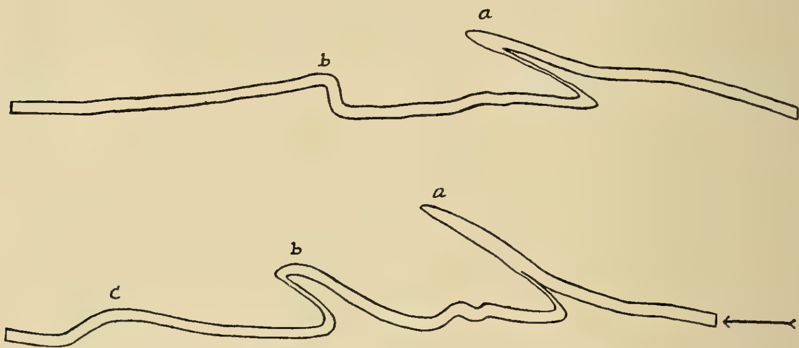


FIG. 4.—Successive stages in the development of overfolds. Top figure after 6 inches of shortening; bottom figure same after 8 inches of shortening. Fold *a* formed first. Fold *b*, which started as an underthrust, has changed into a pronounced overthrust. Note the thinning of the under limbs. With still further compression flexure *c* developed into a strong overfold.

to develop underfolding, overturned folds resulted. On the other hand, when the blocks were placed in the opposite positions, so that the layers sloped downward from the pressure block to the resistance block and the active force was applied somewhat above the fold, no trouble was experienced in developing overfolds.

It was found also that the nature of the materials influenced to some extent the direction of yielding. When the materials were relatively competent and brittle (sand, clay, and plaster), and the mass was deformed by faulting rather than folding, overthrust and underthrust faults resulted in more or less equal proportions. Wedge faults developed in some instances. But in the plastic models it was found almost impossible to produce underthrust

faults. There was, however, one rather unusual case where, in the early stages of the deformation, an underthrust formed on one side of the model and an overthrust on the other side. After further compression the underthrust was truncated by an overthrust and the overthrust cut by an underthrust (see Fig. 16, p. 510).

Hobbs has expressed the belief that overturned folds, though rare, may be developed in special cases (backfolding of anticlines) where the material being folded thins away from the active force.[1] In the experiment by Daubrée which he cites, an overturned fold developed in unmistakable fashion, just as in general there is little difficulty in producing overfolds. Our experience has been that the greater difficulty lies in producing underfolds. To put the case of underfolds vs. overfolds to a more severe test by utilizing this same principle, a layer was prepared to reverse these conditions, by having it thin steadily toward the pressure block. This should have the effect of producing weakness near the pressure block, and seemingly should be most favorable for the development of an underturned fold. Instead of an underfold, the resulting wrinkle was a decided overfold on one side of the model, and a symmetrical upright fold on the other.

From the usual behavior in this series of experiments, it would seem that in the more brittle and elastic materials, where faulting occurs without much preliminary deformation, the fracture may go either way without great preference for the overthrust, but in more plastic, incompetent material, where portions of the mass yield readily to moderate differences of stress and the phenomena are those of folding preceding fracture, overfolding is far more likely to occur than underfolding, and the preponderance of overthrust faulting over underthrust faulting is still greater.

VARIATIONS IN FOLDING

With varying overburden.—To see what effect variations in the amount of overburden would have on the type of folding produced, a series of models was prepared of equal parts of paraffin and vaseline, and of equal thickness. These were deformed at the same rate of speed but with different overburden.

[1] W. H. Hobbs, "Mechanics of Formation of Arcuate Mountains," *Jour. of Geol.*, Vol. XXII (1914), pp. 185–87.

The first model was compressed without covering. Since the material was quite plastic, a high overfold developed. This suggests that horizontal compression near the surface of the earth, where the overburden is not great, would be likely to produce large simple folds, rather than smaller complex folding.

In the second experiment the layer was covered with sand only, so that there were not more than 10 or 15 pounds of total overburden, uniformly distributed over the model whose dimensions were $20'' \times 5\frac{1}{2}'' \times \frac{1}{2}''$. In this case the folding was more complex. The principal anticline developed nearer the pressure block; did not go so high as in the previous experiment; was subjected to a series of minor undulations; and in addition, a small thrust fault developed.

In the third experiment the overburden totaled 50 pounds, uniformly distributed. In this case the folding did not rise quite so high as in the second, but was more distributed along the length of the model A thrust fault which developed on one side of the model had a greater displacement than that in the second experiment.

In the fourth experiment a weight of 190 pounds was placed over the model. The results of compressing this model were quite different from the others. There was only a very minor amount of folding, but on the other hand, faulting was important, and there was some thickening of the layer. The deformation was not confined to any particular zone.

Thus the general result of increasing overburden was a tendency to produce more complex and more distributed folding, more faulting, and more thickening of the material. Since it is easier for a series of small folds to hold up a heavy covering than it is for one large fold, it is not difficult to see why the folds should not go so high when the overburden was greater. Similarly, in nature, folds should probably be smaller and more widely distributed in depth than at the surface. The occurrence of faults in the specimens where the overburden was greatest is startling, as it is generally supposed that, with increasing depth, folding gradually takes the place of faulting. Faulting, however, is a much easier type of deformation under quick acting stresses than folding, and may therefore be a more natural way of taking up the shortening in cases where the resisting pressures of overburden tend to prevent the upbowing necessary in folding.

But in the earth, where the stresses operate more slowly and the greater length of time allows more extensive readjustment by recrystallization, it is less certain that faulting should increase in relative importance with increasing depth. Down to considerable depths,

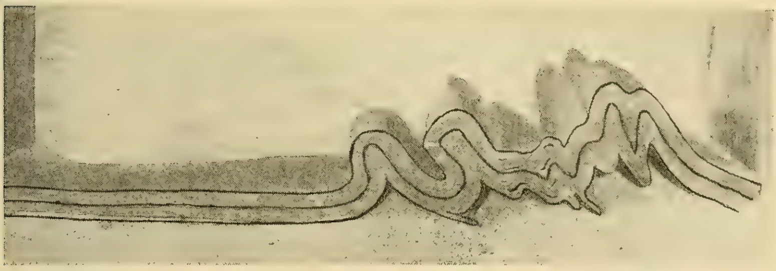


FIG. 5.—Model of six layers. Layers consisted of equal parts paraffin and vaseline except layer 4 (3 par., 1 vas.). Original length $25\frac{1}{4}$ inches; shortened 9 inches. Ink line follows base of layer 4. Pressure from the right.

FIG. 6.—Original length 22 inches; compressed $4\frac{1}{8}$ inches. Layers 1, 3, 5, 7, 9 and 11 were 1 paraffin, 1 vaseline. Layers 2, 6 and 10 were 1 par., 2 vas. Layers 4 and 8 were 3 par., $\frac{1}{2}$ vas., 1 plaster. Cavity developed under gentlest of the three anticlines. Folds developed first near the two extremities with less deformation in the middle portion. Pressure from the right.

this might be the case, but at still greater depths faulting would doubtless gradually be replaced by the phenomena of rock flowage.

With layers of uniform competency.—In the models having several layers a variation in the folding from the top layers to the bottom ones was generally very marked (Figs. 5–8). Anticlines became less pronounced in lower layers, both when the folding was of the

parallel type, and when there was considerable thickening on the crests of the anticlines. Conversely synclines grew larger with increasing depth, but the change in the case of the synclines was not so marked as in the case of the anticlines. Thus it might appear

FIG. 7.—Same model as Fig. 6, compressed to total of 8 inches. Cavity has disappeared with more intense folding. Other tiny cavities have developed where the folding is gentle. The overturned fold of Fig. 6 has become nearly upright.

FIG. 8.—Reverse face of Fig. 7 model. Pressure from the left. Vertical variations of folds.

that the shortening was decreasing with depth, but the apparent difference was made up by faulting in the lowest layers. Anticlines which have rounded curves near the upper surface pass into pointed folds beneath. This is one step in the dying out of folds. Slippage between layers has played an important part in the process.

Cavities between the layers of the anticlines and the synclines were most common where the folding was least intense (Fig. 6). It is not certain, however, that this principle can be applied to the location of such ore deposits as the saddle reefs of Bendigo, for there the access of solutions and other factors doubtless play an important part. Pockets of oil and gas should be more abundant where the folding is very gentle.

Competent layers between incompetent.—Experiments were performed in which fairly competent brittle layers were inserted between very plastic layers. The former were made with 4 parts of

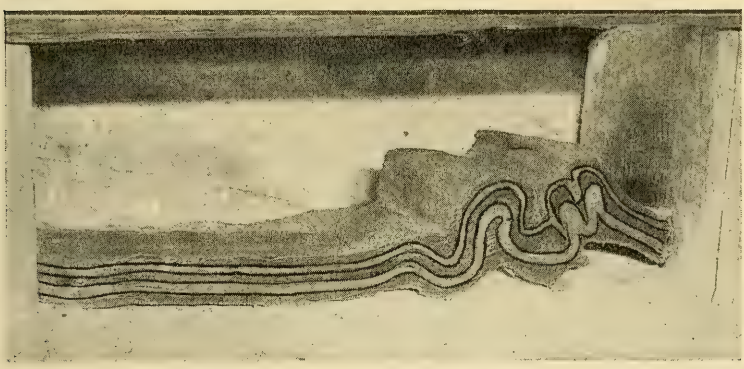


FIG. 9.—Original length 25 inches; compressed 8 inches. Layers 1, 4 and 6 were 1 paraffin, 12 vaseline. Layers 2, 3 and 5 were 1 par., 1 vas. Layers 2 and 3 appear as one. Softer layers much distorted. Strangle folds developed.

paraffin to 3 of vaseline, and the latter with 3 parts of vaseline to 1 part of paraffin. It was found that after compression had shortened the models by a few inches, the competent layers folded without much internal distortion, but that the plastic layers were tremendously distorted, being thickened on the crests of the anticlines and in the troughs of the synclines, with much stretching on the limbs (Figs. 9 and 10). In the early stages of folding there was a general correspondence between the anticlines and synclines in the layers of different competency, but, with further compression, the brittle layers developed minor folds which were entirely at variance with the surfaces of the plastic material. This was possible because of the great thickening of the plastic layers whose ready yielding greatly

facilitated the adjustments necessary in this type of folding, and thus constituted zones of accommodation.

In several cases a plastic layer between two competent layers pinched out completely for a short distance. This is comparable to some of the occurrences in the Alps where a layer has been so much thinned that it has completely disappeared from the section. Strangle folds which are also found in the Alps, and in a few other localities, were reproduced in the models (Fig. 9). In some cases the

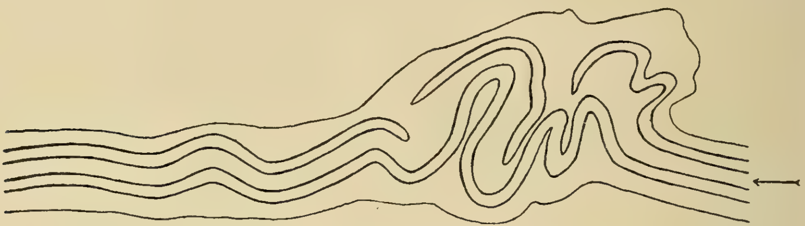


FIG. 10.—Same model as Fig. 9 after 12 inches of compression. The upper competent layer has been pulled apart by upward flowage of the plastic material beneath.

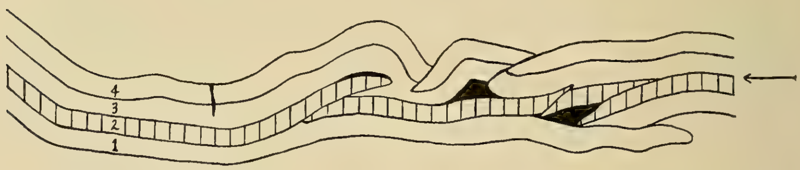


FIG. 11.—Layer 2 made of plaster; other layers 3 paraffin, 1 vaseline; 23 inches compressed to $14\frac{1}{2}$ inches in 30 minutes. Fracturing of the strong layer (No. 2) caused considerable fracturing above and below. Open spaces represented by black. Note the slight degree of folding in the bottom layer.

competent layers were faulted, so that there were two disconnected ends, but the fault was largely obscured because the plastic material flowed in.

Rigid layer in the midst of plastic material.—Where a layer of plaster of Paris was inserted between moderately plastic layers somewhat different results occurred. Since the plaster of Paris was too brittle to be folded, it invariably broke. In breaking it caused considerable fracturing of the surrounding layers (Fig. 11). Conditions of this sort may account for an unexpected amount of fracturing in some types of sedimentary rocks which would normally be more

folded. In one case an anticline developed above the plaster layer and a somewhat fractured syncline below. This behavior was apparently due to a thickening of the intervening plaster by slice faulting. The whole mass was so much broken that it was difficult to trace the individual planes. Such an occurrence might easily cause confusion in an oil field by changing the surface anticline into a syncline below. In general, where an especially brittle formation occurs between more easily folded formations, structural changes in depth are very likely to occur.

ISLANDS OF RIGID MATERIAL

Sedimentation has frequently occurred in seas where islands or submerged reefs of metamorphic or igneous rock have stood above the general level of the sea bottom in such a way that the sediments

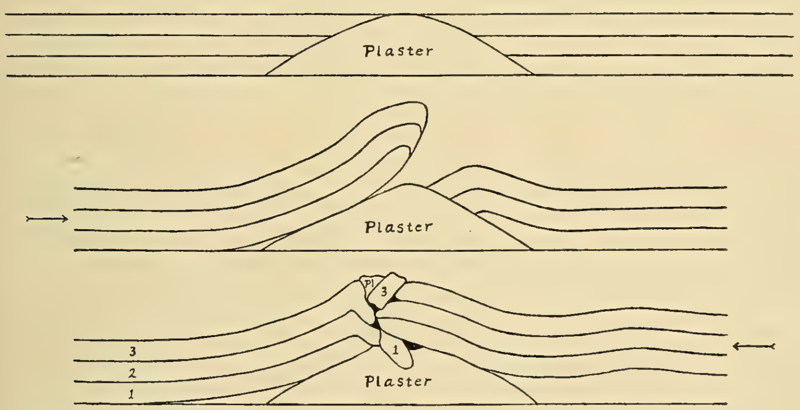


FIG. 12.—Plaster island in midst of weaker beds. Bottom layer 2 paraffin, 1 vaseline; middle layer, 1 par., 1 vas., 1 plaster; top layer, 4 par., 1 vas.

East side of model (middle figure): Beds nearest pressure block turned under and slid upward over the rigid plaster.

West side of model (lower figure): Beds on both sides turned under and sliding upward carried some of the plaster with them.

were deposited all round them, and in many cases eventually covered them. In order to get some idea of what might be the effect of such a buried crystalline mass upon folding which subsequently affected the region, compression experiments were tried upon a model which consisted of a mass of cement with outward sloping sides, placed within a succession of plastic layers (Fig. 12). Compression

of this model caused the plastic layers to be thrust up over the cement block and produced very complex faulting and folding above it. Another way to test the same idea was to place a block of cement in the sand below a portion of a model. The effect of this block was to cause an especially pronounced fold to occur over the block, in spite of the fact that this was placed on the end opposite from the active pressure.

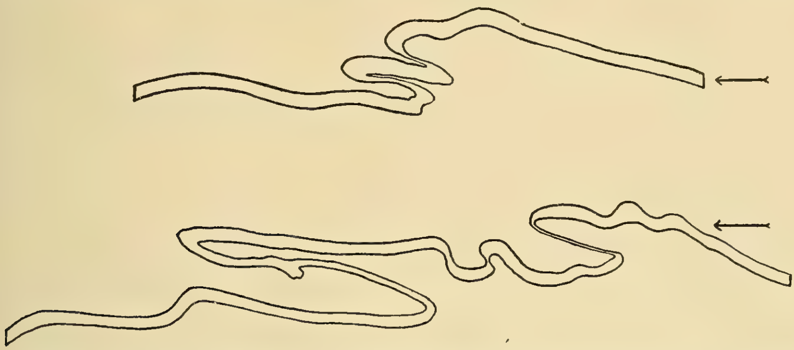
Since in nature there undoubtedly are cases where such former islands of resistant crystalline rocks are not exposed at the surface, it would seem probable that complicated dome structures might be explained in this way. R. C. Moore has reported that folding in eastern Kansas has tended to follow an old buried granite ridge, which formed a sort of island in the later Paleozoic sediments.[1] In a similar way some of the small ranges of central Montana and Wyoming may be due to causes of this sort, and even the Black Hills of South Dakota may owe their origin in part to this selective deformation.

ALPINE OVERFOLDS

Several attempts were made to reproduce the overfolds, or nappes de recouvrement, of the Alps by applying rotational stresses to models in which competent layers were placed between incompetent layers, since this seemed to represent the conditions in the Alps, where competent limestone formations are interbedded with less competent shales. These experiments, however, did not succeed in developing Alpine structures in this way, since the resulting overfolds were overturned only to a small degree, and continued pressure only served to cause folding elsewhere, and to produce a vertical rising of the overturned folds. As it is not easy to see how conditions in the Alps could have been more favorable for producing overfolds than these experimental conditions, one may well wonder at the current European interpretation which assigns such tremendous extents to the nappes. But if low-angle overthrust faulting enters largely into the horizontal shifting of material, these nappes take on a quite different aspect.

[1] Raymond C. Moore, "Buried Granite in Kansas," *Bull. Geol. Soc. Am.*, Vol. XXXIII (1922), pp. 96–98.

A better way to reproduce overfolds was found, though natural conditions do not appear to be so well represented. Single layers consisting of equal proportions of vaseline and paraffin were prepared in long thin sheets whose dimensions were approximately 22″×5″×2″. By compressing these long thin models, overfolds somewhat resembling the structure sections of the Alps were produced (Figs. 13 and 14). These overfolds had their lower limbs very much drawn out. In at least one case the "tete," or head, of the



FIGS. 13 and 14.—Recumbent folds simulating nappes de recouvrement. These are overfolds whose lower limbs have been drawn out thin. Compare with Hobbs' contention that in overfolds the upper limbs should be thinned.

fold was curved down toward the undeformed portion beyond the fold (Fig. 15).

In some ways these folds were very different from the Alpine folds, as they have commonly been interpreted. According to the standard European interpretation the lower folds were formed first, and were covered successively by more overfolds coming from the south, the direction of the active force. But in these experiments the reverse was always true. The overfolds, as a rule, formed first next to the pressure block, and the later ones farther and farther away. This was in general the earlier experience of Willis.[1] In no case was an overturned fold pushed completely over the one beyond it. By the time that one had been pushed to the point where the

[1] Bailey Willis, "Mechanics of Appalachian Folding," *Thirteenth Ann. Rept., U.S. Geol. Survey*, 1891–92, Part II, pp. 211–82.

under limb was on the point of breaking, another fold formed in front of it, and so on. By continuing the compression sufficiently, faulting took place. In one case (see Fig. 4, p. 498) an underturned fold, which started near the end of the model farthest from the active force, was eventually changed into an overturned fold, due to the advance of the overturned folds from the other end. Such a general tendency and behavior may account for the overfolding being practically all in the same direction in some ranges.

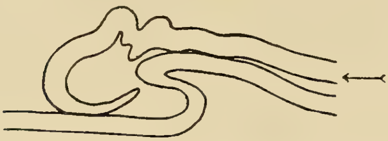


FIG. 15.—Broken overturned fold. The front of the fold has turned under, resembling the so-called head of a nappe. Two nappes in different stages of development formed by compressing a single layer of equal parts of paraffin and vaseline.

Conclusions in regard to Alpine structure which might be drawn from these experiments are, in the first place, that the folds may perhaps have developed in a different order of succession from that commonly inferred, the upper nappes possibly having formed first. Also in the place where one nappe is supposed to have completely overridden another, it is perhaps most reasonable to infer that this was accomplished rather more by faulting than by folding.

DEVELOPMENT OF LACCOLITHIC INTRUSIONS IN FOLDED FORMATIONS

The term laccolith is ordinarily applied to structures in which a fairly thick mass of intruding magma has arched up a dome. While the floor of this structure is rarely seen, it is commonly inferred to consist of more or less flat-lying sedimentary rocks, cut only by the dike or dikes which represent the upward paths of the igneous material. Some of the experiments suggested ways in which a type of laccolith could be produced with folding occurring both above and below the igneous intrusion. In one experiment a thrust fault occurred on the steep side of an asymmetrical fold. This thrust did not cut through the top layer. If some magma had made its way up along this fault plane, it would have tended to spread out beneath the top layer near the top of the anticline. Partial erosion could then have revealed an apparent laccolith. This, however,

would probably be of only modest dimensions, and might be classified as a phacolite.[1]

In another case a wedge fault occurred in the lower layer on the limb of an anticline. Since this wedge faulting took up some of the shortening of this layer, it was not arched as high as the upper layers and thus left a cavity between. In nature, a potential cavity might be produced similarly, and magma, making its way up along the wedge fault, and between the layers, might help force the production of the cavity and fill it. Such an occurrence could also produce a structure which had all the surface appearance of a common laccolith.

Rupture by tension on the crest of an anticline sometimes was confined to the lower layers of a model. In such cases cracks developed right across the individual members in the lower portion of the model. Along these cracks an igneous intrusion could force its way up as far as the unbroken layer and spread out below that layer.

INCIDENTAL OBSERVATIONS ON FAULTS

Dying out of faults.—In nature faults are known to die out upward, downward, and laterally, but it is often impossible to see what happens in the space between where there is a distinct fault and where there is no fault. In the experiments faults of small displacement frequently played out both vertically and horizontally. In some cases the scarp of an overthrust became lower and lower transversely across the model till it disappeared in favor of the unbroken layer. Still more frequently the layers below an anticline were found to be faulted while the top layer was not affected. In another case the top layers were faulted and the bottom layer was merely folded (Fig. 16, p. 510). As sections could be cut into the models at any place desired, it was not difficult to observe the manner in which these faults died out. In general the most common manner was by a thickening and thinning of the layers in such a way as to take up the waste space. A slight local bending after the fashion of a minor monoclinal flexure in many cases facilitated the accommodation. Another method was by the formation of a cavity at the top of the fault on the downthrow side.

[1] Alfred Harker, *Natural History of Igneous Rocks*, 1909, pp. 77–78.

Wedge faults.—The phenomena of wedge faulting occurred rather frequently in the models. These faults, however, were of rather small displacement because it is not easy for the wedges to move for any great distance under the conditions of the experiments without having the whole mass broken across by a general thrust fault.

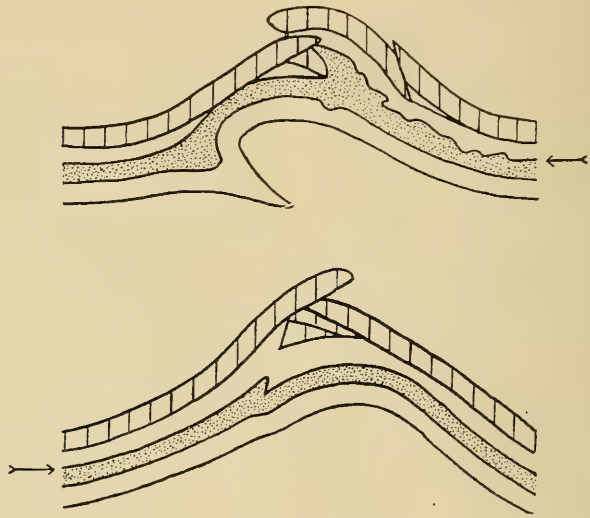


FIG. 16.—Top layer faulted while bottom layer merely folded. Opposite sides of same model. A section cut through the middle of the model showed more shortening in the two lower layers. The nature of the deformation changed rapidly from place to place. Two stages of faulting, an overthrust on one slope and an underthrust on the other; then reversal of the process.

Angles of thrust faults.—In considering the angles of thrust faults, W. H. Bucher in his recent paper on "The Mechanical Interpretation of Joints" lays great emphasis on the plasticity of the deformed material and the depth at which it is deformed.[1] Engineering experiments illustrate clearly that the angle of fracture depends on the nature of the material deformed, and in nature the angle of thrust faulting presumably should be influenced by this factor. If nothing else influenced the angle, low-angle faulting might be found where deformations occurred near the surface and where the formations were brittle. High-angle faults should be

[1] W. H. Bucher, *Jour. of Geol.*, Vol. XXVIII (1920), pp. 707–30, and Vol. XXIX (1921), pp. 1–28.

found in the less brittle materials deformed at greater depth. Field observations only in part substantiate this idea. Since the mechanical principle is doubtless correct, the anomalies must be explained. Some suggestions as to the cause of high-angle faulting were obtained from these experiments on folding.

High-angle thrust faults.—By using layers of paraffin and vaseline, which would fold before breaking, thus representing the conditions of folding not far from the earth's surface, fairly numerous high-angle faults were developed. The conditions determining these steep faults were found to be somewhat varied. In one or two cases a crack developed in the upper side of an asymmetrical anticline, due to tension, and this crack changed into a thrust fault with its dip well over 45° (Fig. 17). Secondly it was found that high-angle thrusts may develop on the limbs of anticlines. In such situations the transmitted forces operate nearly parallel to the sloping surface of the limb, and therefore should a fault develop at 45° to the applied forces, it may be inclined as much as 90° from the horizontal. In several cases a fault developed on the side of an anticline, and as compression continued, the fault ceased to grow, while the anticline became more tightly folded. In such cases the angles of the faults were low at first, but gradually increased as the sides of the anticlines grew steeper, and in one case they approached verticality.

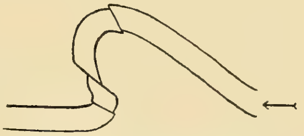


Fig. 17.—Break thrusts on stretched lower limb of anticline. The higher up on the fold, the steeper the angle of fracture. Thrust near crest has angle of 57°.

Low-angle thrust faults.—In the other direction the very great potency of rotational stress in lowering the angle of thrust faulting even down to horizontality, as exemplified in the great overthrusts, has been pointed out by the senior author in a paper on "Low Angle Faulting."[1] This rotational stress may be developed in a variety of ways.

Faulting in sand and clay.—While testing the qualities of the sand used in enclosing the models, in order to determine what effect they would have on the deformation, some rather surprising results came to light. A layer of dry sand 3 inches thick, with flattened

[1] R. T. Chamberlin and W. Z. Miller, *op. cit.*

surface, was placed in the bottom of the compression box. After pushing the end of the sand forward for about 1 inch, a terrace-like development was produced whose scarp appeared about 5 inches from the pressure block; 2 inches of pushing produced a second terrace scarp 3 inches farther out, the terrace being correspondingly uplifted; 4 inches of compression developed a third terrace 1 inch in width. With further pressure the entire mass moved forward.

The cause of these terrace-like uplifts was investigated in several ways. Straws were stuck into the sand between the pressure block and the zone where the first terrace was expected to begin. Upon applying pressure it was found that those straws which were stuck deeply into the sand were bent over away from the pressure block, while those straws which extended but little beneath the surface remained upright. This difference in behavior suggested that the upper portion of the sand moved forward largely as a unit over the lower portion after the manner of thrust faulting in solid blocks.

The nature of this deformation was further tested by placing smoked glass plates in the sand at right angles to the pressure block. In this way some idea could be obtained both as to how much of the sand was moved by the terracing action, and also its direction of movement, because the moving sand rubbed against the plates and removed the soot in streaks. The results of this method were not always very satisfactory, but some cases showed clearly that there had been thrust faulting with the dips of the slippage, as indicated by the movement of the sand grains, ranging from 20° to 35°.

Clay was substituted for the sand and pushed in the same manner. Similar terraces also developed in this material. Since clay will stand in slopes better than sand, sections were cut in it with a knife at right angles to the terraces. In this way the actual fault planes could be observed for a short time, till the clay broke off and covered them. The angles of these faults varied from 9 to 29 degrees. In general the angle seemed to become lower after faulting had progressed for a little distance.

This thrust faulting in sand and clay suggests that some of the escarpments found in unconsolidated mantle rock in the basin ranges of Nevada and Utah may have been the result of thrust faulting rather than normal faulting.

REVIEWS

British (*Terra Nova*) *Antarctic Expedition, 1910–1913. Glaciology.* By C. S. WRIGHT AND R. E. PRIESTLEY. Quarto, pp. xx+487, figs. 481, plates 417, maps XIV. London, 1922.

This important work is the joint product of a physicist, C. S. Wright, and a geologist, R. E. Priestley. The chapters on "Snow and Its Derivatives"; "Ice Crystals Formed from Vapour"; "Crystalline Structure of Ice"; "The Mechanism of Glacier Motion"; "Ablation and Thaw, with Particular Relations to Antarctic Glaciers"; and "A Review of the Causes of Glacierisation" were written by Wright. Those on "Classification of Land-Ice Formations"; "Structure of Glaciers"; "The Antarctic Icefoot"; "Antarctic Fast-Ice"; "Antarctic Pack-Ice"; "Antarctic Icebergs"; and "Geological Climates of the Antarctic" were prepared by Priestley, and that on "Ice Formations Characteristic of an Advanced Stage of the Glacial Cycle" by the two jointly. This division of labor necessarily implies some degree of independence of work and of textual treatment, but just how much can probably best be learned from the text itself. A general concurrence of views is claimed. The reader will do well, however, to note the authorship of each of the chapters as he reads them, for he may find that one sees through the spectacles of the laboratory, the other through the binoculars of the field. The studies actually made are, in the main, regional (Victoria Land), but the treatment has wisely been given continental breadth by comparisons between all known parts of Antarctica. There is thus brought together a vast amount of material relative to the glacial phenomena of a great region only imperfectly known heretofore. It will only be possible to notice a few of the more outstanding features. We shall therefore feel at liberty to disregard the order of subjects and touch as most convenient the themes of most concern to students of geologic climates.

As a background for more special subjects, let us first notice a tabular summation of what are held to be the known glacial periods of geologic history (p. 418).

Some glacialists would add to the periods listed and some would perhaps question certain periods included, but the table seems to fairly represent the weight of competent opinion. The main things to be

emphasized are that they range over almost the whole of known geological history (Proterozoic to Pleistocene) and that the intervals between them are much greater than the glacial periods themselves. There follows this table a summary of what is now known of the geologic climates of Antarctica (p. 419) the gist of which is here given because of its special interest.

TABLE OF GLACIAL PERIODS

Main Proved Glacial Periods	Local Glaciation	Countries Where Developed	Remarks
1. Huronian.........	....	Canada	Pre-glacial surface an undulating surface of low relief.
2. Proterozoic	....	India Africa Norway	Possibly two separate glacial periods combined. In Norway probably low land as pre-glacial surface.
3. Proterozoic or Lower Cambrian..	....	China Australia	Middle latitudes N. and S. of Equator. Australian geologists claim this Ice age in Australia as Lower Cambrian; United States geologists insist that here also it is Proterozoic.*
4. Devonian	....	South Africa	
5. Permo-Carboniferous...........	....	Australia S. Europe Brazil Africa India	Middle to low latitudes. Seasonal climate in N. and S. Marked inter-glacial periods. Developed on plateaux of low relief and mountains not particularly glaciated.
6.	Cretaceous	....	
7. Pleistocene	....	World-wide	Particularly effective in high latitudes. Several inter-glacial periods. Chiefly developed on high plateaux. The only glaciation yet proved in Antarctica. Apparently began there in Eocene or Oligocene times, and has been interrupted by inter-glacial periods.

* Information has recently been received from Australia to the effect that Professor David, who has re-examined the exposures, now agrees with the United States geologists in their view of the Proterozoic age of these deposits.

Respecting the climates of the pre-Cambrian ages little evidence has been found in Antarctica. The presence of limestone and graphite seems to imply at least moderate warmth at the specific stages they represent,

but of course not necessarily of all stages of the terranes in which they are found. Erratic blocks of sandstone containing Radiolaria perhaps imply the same.

In Cambrian times, limestone with Archaeocyathinae and calcareous algae are found in widely separated localities. "Huge reefs of coral and algae living in association—much as the coral reefs of today, but probably of even greater size—must have existed through some degrees of latitude at least." "The occurrence of the Archæocyathinæ and Epiphyton on a large scale in Cambrian Antarctic seas is (if any faith may be placed in the principle of the elucidation of past climates by analogy with the conditions under which the present allied faunas of the world flourish) definite proof of a fairly high temperature in the Cambrian Antarctic seas" (p. 422). "Yet, it must be admitted, a comparison between Antarctic and Australian forms of Archæocyathinæ brings to light the fact that all Antarctic forms yet discovered are either embryonic or dwarfed. They bear the stamp of having had to struggle for their existence in rather an unsuitable environment" (p. 423).

Respecting the climate of Silurian times, no reliable information is reported. Fish identified as Devonian have been found in shales, but their climatic import is not regarded as decisive, except in a rather broad sense.

The most interesting of all Antarctic formations climatically is the Beacon Sandstone, and fortunately it is the one most widely exposed in South Victoria Land. It contains a relatively large quantity of woody or carbonaceous matter or of imprints, including plant fossils and beds of coal. These are distributed through a considerable thickness of the formation. "The type plant of the Glossopteris flora has been discovered in great abundance at the Beardmore Glacier, within a few degrees of the Pole. There can be no doubt at all that, throughout a considerable portion of this time, the climate of large regions of this part of Antarctica was such as to favor the development of a relatively prolific flora, though one of a type which is associated in other countries with evidence of the great Permo-Carboniferous glaciation" (p. 424). As is well known, Antarctica is regarded by many as the original center of distribution of the Glossopteris flora. According to this view the formation in Antarctica was at least as early as the glacial formations of Australia, India, South Africa, and South America, which also contain the flora.

An ample Jurassic flora was found by the Swedish Antarctic Expedition at Hope Bay in West Antarctica and identified by Gunnar Anderson and by Nathorst. From the climatological point of view, it is said the collections might have been gathered on the coast of Yorkshire.

Marine formations of Cretaceous age were found in West Antarctica and Graham Land by the Nordenskjold Expedition, containing fossils identical with those of the same age found in India.[1]

The occurrence of dicotyledons in marine sediments of Oligocene or early Miocene age, in West Antarctica, seems to imply a temperate climate, but this evidence and that of the associated marine fossils are thought to be not altogether decisive. "Considering all the evidence together, we are perhaps justified in visualizing conditions similar to those at present existing near the outer limits of the temperate zones of to-day, though the presence of some 50 sub-tropical forms and only twenty temperate forms in the flora suggests a somewhat warmer environment" (p. 433). The possible existence of glaciation farther south at these or earlier times (Eocene) is suggested, but the weakness of the grounds for the suggestion is also noted.

Late Tertiary time in Antarctica is said to have been characterized by great eruptions of volcanic material. At three localities in this region true erratics occur, from which, as also from supporting evidence of other sorts, it is inferred that glaciation was present during some part of this time.

The evidence bearing on the initiation of the present climatic state is said to be less complete and satisfactory than could be desired. It cannot well be sketched briefly, and the reader is referred to the details offered.

In summation, it is inferred that, incomplete as the record is, it "is eloquent of the fact that, to all appearance, any *glacial conditions have been the exception and not the rule in Antarctica*." This conclusion, the reviewer believes, is in general harmony with the testimony of the geological formations within the Arctic Circle, where the stratigraphic and paleontologic evidences are more ample and explicit. Now that this mass of evidence from the South Polar circle has been piled upon the still greater mass of similar evidence, long known, from the North Polar region, as well as the important new testimony added recently by Lauge Koch[2] and A. C. Seward,[3] there ought to be no longer any disputation over the former existence of warm climates in polar latitudes for long periods between the known glacial periods.

[1] The authors fail to cite the evidence of similar import found in a collection of fossils made by the artist Stokes and determined by Stuart Weller, *Jour. Geol.*, Vol. XI (1903), pp. 413–19; especially p. 414.

[2] Lauge, Koch, "Stratigraphy of Northwest Greenland," *Meddelhena fra Dansk Geologiske Forening*, Bd. 5, No. 17, 1920, and later papers.

[3] A. C. Seward, *A Summer in Greenland*, Cambridge University Press, 1922.

If next we look over all the outstanding features of Antarctic glaciation, as set forth in this report, in an endeavor to catch the one which, aside from superior dimensions, most distinguishes it from the glaciations of the Arctic regions and the high altitudes of mid-latitudes, we think it will be found in the great display of *the initial and growing stages* of glaciation, as distinguished from *the mature and vanishing* stages. There are unparalleled snow-fields and névé-fields; and great displays of the lower orders of solidification of the glacier type; but the higher orders of compact glacier ice are remarkably scant. A part of the explnaation is well recognized, though perhaps not emphasized as much as it might well be. The collecting grounds are large, the mean slope is gentle, the average temperature low, melting almost absent, consolidation by granular growth slow in the absence of much water, and the mean motion meager, so that, before the great mantle has reached a highly compacted stage and entered upon much forceful shearing work, the sea level is reached and the partially solidified mantle is floated away in the form of great tabular icebergs. These are so porous in appearance that they are sometimes called "snowbergs." This term overstrains the facts of the case, but it helps correct the intimation that Antarctica displays the full cycle of a typical glacier. We shall have occasion to return to this in reviewing the subjects of glacial structure and glacial motion. Antarctica tells with wonderful impressiveness the story of a glacier's birth and early growth, but the story is cut off in early youth before the stiffer work of the glacier's maturity has begun. Some of the overenthusiastic expressions of the authors about the superior instructiveness of Antarctic glaciation need to be qualified by emphasizing Antarctica as a field of surpassing opportunity for the study of snow and snow-fields, of névé and névé-fields, of icebergs, and of sea-ice, but by emphasizing also that it falls far below the Arctic lands and some mid-latitude tracts in facilities for the study of the more solid phases of glacier ice and that forceful shearing action which grinds rock-flour, scores imbedded material and the glacier's bed, and thus leaves the distinctive marks by which ancient glaciations are chiefly identified.

In view of the unparalleled resources of the Antarctic field for the study of snow and névé, it was both natural and appropriate that the early chapters of the report should center on the formation of snow crystals, their growth into the granules of the névé, and the transition thence into glacier ice. It is natural also for the reader to expect, in view of the opportunity, a discussion of the growth of granules of snow into névé and of névé into glacier ice of like high order. In most respects this expecta-

tion is realized so far as the observational phases of the subject are concerned. The special studies in this line cover a wide range and much new matter is added to previous knowledge. In extending the treatment, however, to generalizations and interpretations involving past work and previous views, there appear some strange misconstructions. As these take the form of statements leading up to new interpretations in such a way as to form their background and basis, they require notice to forestall confusion respecting the main subjects. For example, in the approach to a new explanation of the growth of snow granules, the following statement is made:

> In the Antarctic (as elsewhere), where a snow-drift or other mass of snow crystals persists for a certain time, a change occurs in the size and shape of the individual crystals, this change (at least within certain limits) being progressively toward an increase in the mean size of the crystal. Broadly speaking, this modification probably takes place by the elimination of those crytsals which are of least size, and by the addition of their mass to the larger crystals. . . . . This dependence of the rate of change upon the temperature is supported by laboratory experiments,* and from laboratory experiments we also know, at least for temperatures slightly below freezing point, that the rate of the change increases with the pressure applied.† These two facts have given rise to the theory that the growth of certain crystals at the expense of others takes place only when the snow or ice is close to the melting temperature [pp. 45–6].

This last statement has the force of an intimation that the growth of snow crystals much below the melting point was not a factor of previous views and that these left an unoccupied field to be exploited. But this intimation is quite far from the truth. In the paper of Chamberlin, cited as giving experimental evidence of granular growth, it is said (pp. 193–4):

> The microscopic study of new-fallen snow reveals the mode of change from flakes to granules. . . . . If measured systematically from day to day, the larger granules taken from beneath the surface of coarse-grained snow are found to be growing. In a series of experiments to determine the law of growth, it was found that when the temperature of the atmosphere was above the melting point, the growth was appreciably more rapid than when the air was colder, but that there was, on the average, *an increase under all conditions of temperature.*

The italics are those of the paper cited, which was written twenty years ago. The basal fact thus demonstrated and emphasized has been

* T. C. Chamberlin, "A Contribution to the Theory of Glacial Motion," p. 193, Decennial Publication. University of Chicago, 1904.

† Hess, *Der Gletscher*, p. 31 *et seq.* *See also* Appendix to the report. [Footnotes the author's].

extensively taught ever since, at least in America. The microscopic examinations of the granules referred to were carried out by C. S. Peet and E. C. Perisho daily throughout the rather severe winter of 1893–94 as experienced at Chicago. The granules and their whole immediate environment were often much below the freezing point for days together. Furthermore, in the paper cited, there was also a discussion of the effects of the penetration of the snow fields by the "winter wave" of the arctic region, and mean temperatures as low as $-25°$ C. were had under consideration. But disregarding these explicit postulations of granular growth at temperatures far below the freezing point, the writer of this part of the report continues:

The supposed mechanism seems to be a progressive melting under pressure where the points of the crystals touch one another, and a flow of the fluid thus produced to other places where the pressure is less. This might afford a reasonable explanation of the cause of growth of the larger crystals at the expense of the smaller in a mass of snow composed of individual crystals at temperatures near the triple point, for the local pressure per unit area must be greater for the smaller crystals, and therefore a greater amount of melting should take place at their surface. It does not, however, afford any explanation of the fact that crystals do slowly grow in size, even at temperatures well below zero Fahrenheit, where the pressure due to the superincumbent foot or so of snow is utterly insufficient to cause any significant local increase of pressure.

The theory of yield and growth by pressure-melting at points of contact has long been held for the range of temperatures to which it is applicable but not urged, so far as we know, for any other. As growth at lower temperatures of any degree had long been assigned to evaporation and re-accretion, the last sentence has no pertinence except for the author's unwarranted predication of the view "that the growth of certain crystals at the expense of others takes place *only* [italics the reviewer's] when the snow or ice is close to the melting temperature."

The reviewer, at least, had never previously heard of a theory of granular growth so restricted. On the contrary, the following from Chamberlin's paper above cited has had much currency:

To follow the process [of granular growth] it should be noted that the surface of every granule is constantly throwing off particles of vapor, that the rate at which the particles are thrown off is dependent, among other things, on the curvature of the surface, being greater the sharper the curve; that the surfaces of the granules are at the same time liable to receive and retain molecules thrown from other granules; and that, other things being equal, the retention of particles also depends on the curvature of the surface but in a reversed sense, the less curved surface retaining more than the sharply curved one. Under these laws,

it is obvious that the larger granules of smaller surface curvature will lose less and gain more, on the average, than the smaller granules of greater curvature. It follows that the larger granules will grow at the expense of the smaller [p. 194, "Contribution to the Theory of Glacial Motion," T. C. Chamberlin, 1904, the paper cited by the writer of the report].

In following the further discussions of the growth of snow granules, the non-technical reader is quite sure to become bewildered by the substitution of the concept of *vapor pressure over the individual granules* for that of *evaporation*, in the author's citation and criticism of views written years ago, especially in the absence of any explicit statement of the sense in which the term "vapor pressure" is used; for example:

As regards the increase in mean size of the crystals, this, as has been pointed out by Chamberlin,[1] should be carried out through the growth of the larger crystals at the expense of the smaller ones, *the action taking place for the reason that the average vapour pressure over a small crystal is greater than that over a large crystal.* [Italics the reviewer's.]

Several passages in Chamberlin's treatise are, however, obscure. Thus the increased vapour pressure over a small crystal is said to be due to the increased curvature of the surface, as is the case with water drops [pp. 118–19].

This is certainly taking extraordinary liberties in citation and in making the mutilated citation the basis of criticism, for no mention whatever is made of vapor pressure in the paper cited. A higher rate of evaporation was assigned to sharper curvature. If the substitution of vapor pressure for evaporation is intended to mean that vapor pressure and evaporation are the same thing, it seems as though that should have been so stated explicitly. Perhaps the reader would like a chance to see for himself whether the obscurity grows out of the original point of view or the substitute.

The need for an explicit statement of precisely what is meant by vapor pressure over the individual granules becomes the more obvious when the ordinary use of vapor pressure comes into use as it does later in giving a list of vapor pressures (p. 267). No hint that another sense of the term "vapor pressure" is here given, but it is evident from the context that the vapor pressures listed are the familiar partial pressures of the water vapor of the atmosphere which are pressures *upon* the granules actuated by the attraction of the mass of the earth.

[1] T. C. Chamberlin, "A Contribution to the Theory of Glacial Motion," Decennial Publication. University of Chicago, Series I, 1904, *Geology.*

Putting aside all special and technical senses of the term "vapor pressure," the facts of the case seem to be these:

If a granule of snow be placed in a suitable receptacle whose inner surface is such as to throw the evaporated particles back, an equilibrium state between the thrown-out and the thrown-back will be reached in time. In this state *neither growth nor depletion takes place.* The out-throw (evaporation) of a small granule with a high curvature is greater than that of a large granule with low curvature. When, therefore, the small granule is shut up by itself in a receptacle until it attains equilibrium, it develops a higher throw-back; i.e., a higher vapor pressure about itself, than does a large granule of less curved surface. But looked at in this way, it is seen that it is the relative evaporation that is the *actuating agency* and that it is the *superior evaporation* of the small granule of higher curvature that gives it the higher vapor pressure when it is suitably *confined.* The vapor pressure is merely a *secondary* effect and is dependent on the *confining contrivance.*

If a granule be placed in a perfect vacuum of unlimited extent—the open sky would be an admirable illustration if the atmosphere about the earth were absent—no such vapor pressure on the granule would arise.

If, instead of either of these ideal cases, we consider the most common of actual cases—that of a granule within a layer of snow—we find it surrounded by the interspaces between itself and its neighboring granules. These interspaces are more or less affected by the varying pressures of the wind and the states of the barometer, and are directly affected by the evaporation of all the granules opening upon them. Out of this complexity let us select for illustration the simple typical case of a large granule opposite a small one. The latter evaporates faster than the former. The first effect then is that each granule receives the particles thrown off from the other, i.e., the large granule receives more granules thrown off by the small granule than the small granule receives from the large granule. After the first action there follows an indefinite series of secondary actions of the to-and-fro type which give rise to a common vapor pressure to which all the other granules opening on the cavity also contribute. This common pressure is controlled ultimately by the gravity of the earth and becomes a factor in the partial pressure of the vapor of the atmosphere. Taken as a whole, it is thus clear that the process of growth under these conditions is primarily that of evaporation and re-accretion, and in this the small granule loses most on the average and gains least. The special vapor pressure on the surface of

the individual granule can scarcely be said to have developed at all, and in so far as it is developed it is a *secondary* product and is so uncertain and elusive as to be beyond tangible evaluation.

If the conveniences of the laboratory have developed technical senses of common terms, that does not abolish the common English of mankind and this should be used in giving great results to the world. Certainly terms of special sense should not be incorporated in literature two decades old.

In treating the phase of granular growth due to melting under pressure, the writer of this section of the report urges the limitations of pressure that may possibly arise in glaciers by reason of their weight as though that were the sole source of melting pressure in Chamberlin's view, and an objection to it (p. 119), whereas, in common with others, he assigned the melting pressure in very explicit terms chiefly to the concentration of stress felt at the point of a granule under pressure which touches another. The intensity of this pressure depends on the ratio of the area of this point of contact to the area which concentrates pressure upon it. Theoretically, the concentration may be indefinitely large. Its actual amount undoubtedly varies through a wide range. The principle is impressively illustrated in the cutting of deep grooves in the rock floor of glaciers.

The singular thing in all this strange treatment of old views is that after all the views advocated in the report are closely similar to those beclouded.

There are some other vital phases of doctrine over which the text prepared by C. S. W. throws similar obscurity or misleading intimations but space does not permit their review here. It is only fair, however, to say explicitly that nothing of the kind has been found in the text prepared by R. E. P.

It has already been remarked that this report gives ample evidence of the superior richness of the Antarctic field in material for the study of the initial and earlier stages of glacier formation and action. One of the quite striking phases on which it would be worth while to dwell, if there were time, is the softness of the snow field near the pole even when the snow appears to be somewhat old. Amundsen reports that he was able to push a tent pole into the snow surface to its full length of 6 feet without difficulty. This seems to imply slow solidification and relative freedom from driving wind action, which solidifies the surface by driving snow spicules into the interstices. It is thus highly suggestive as to conditions at the pole. Of somewhat similar significance is the condition of the upper

snow layers of certain parts of the Ross Barrier, which is practically at the sea-level. The snow particles are said to remain angular for two or three years, which contrasts strongly with the rapidity of snow granulation in warm and moist lands. These and other phenomena of like type clearly show that the processes of granular growth and glacial consolidation sometimes at least proceed with surprising deliberateness. With little doubt, this is due rather to the *persistence* and *continuity* of the coldness and dryness of the region than to any special intensity of these, though they seem to be remarkably intense at times.

In contrast to the unsurpassed display of the snowy, névé, and earlier stages of glacierization, Antarctica offers only an exceedingly scant exhibit of the later and more solid phases of glacier development, particularly those associated with the more forceful and distinctive work of glaciers, such as the bruising, scoring, grinding, and polishing of rocks. Some little emphasis has already been laid on the fact that the sea cuts off what might otherwise be the later glacier history of the main Antarctic ice mantle and substitutes floating careers as derivative icebergs. But this spectacular change, great as it is, does not seem to represent the whole truth, for not a few Antarctic glaciers end on the land and it might be expected that these would take on the same features and activities as the short glaciers, or glacial tongues, in similar latitudes in the Arctic region. A comparison with the latter, in almost identical latitudes, shows that the two are markedly different. In both cases some of these are tongues of the main ice-caps, while some are independent local developments. In the Arctic region the rule is vigorous action in the form of rock-scoring and the development of schistose structure in basal portions of glaciers with abundant insheared débris of all sorts and sizes. In Antarctica, according to this report, such evidences of vigorous forceful action are singularly scant. This appears very fully and explicitly in the chapter on "Structure of Glaciers" (R. E. P) (pp. 223 ff.). Striated bowlders, grooved and planed glacier bottoms and sides, rock-flour, and true subglacial till are almost absent; indeed they are even conveniently spoken of as simply absent. The schistose structure and insheared glaciated material, so wonderfully displayed in the vertical sides and ends of the glaciers of the corresponding Arctic region—particularly about Inglefield Gulf—seem from this report to have no really parallel development in Antarctica. There is, indeed, some banding and "silt layers" in the lower parts of some of the glaciers, but in only one or two cases do the authors find evidence which permits the supposition that the silt could have come from the bottom (see pp. 230–31). Silt layers of surface

origin, as well as layers of coarse débris derived from cliffs, are fully described, but no insheared layers of mingled glaciated material ranging from rock-flour to great striated bowlders are described. From the causal point of view, this is a matter of the utmost importance, for this kind of work is *glacier work par excellence.* But this review has already grown so long that, most interesting as this is, it cannot be discussed here.

The book closes with "A Review of the Causes of Glacierisation" (C. S. W.) (pp. 463–70). As the climax of a discussion of glacierization of the colossal Antarctic type, this dwells too long on causes of climatic variation whose known cycles are so short as to need to be multiplied thousands or ten thousands of times to fit the glacial types, and not long enough on the necessity of selecting causes whose cycles are of the same order as those of the great glacial epochs themselves. Objections to such putative causes, of course, presented themselves. From these the discussion leads up (or down) to the suggestion that the theory of Wegener, if tenable, might solve some of these difficulties. The reader may perhaps sympathize with the reviewer in wishing he had closed the book before he reached this anticlimax. But, without disguising the fact that the report limps badly at times on one of its legs, it is nevertheless a contribution to glaciology of a very high order of value.

T. C. C.

Geology of the Tertiary and Quaternary Periods in the Northwest Part of Peru. By T. O. Bosworth. London: Macmillan and Co., Ltd., 1922. Pp. xxii+434, pl. 26, folders 11, fig. 150.

This volume constitutes a very notable contribution to the geology of South America. It is a departure from the reconnaissance reports of large areas which constitute so large a part of the pioneer geologic literature on South America, inasmuch as it reports in considerable detail and in thoughtful and painstaking fashion careful geological observations within a comparatively restricted area.

The area described is a strip of arid territory twelve to fifteen miles wide, lying between the westernmost range of the Andes and the Pacific Ocean, a short distance south of the Ecuador boundary. The Amotape Mountains to the east, 3,000 to 5,000 feet high, consist of Cretaceous and Paleozoic rocks. From them a great "breccia deposit," or peidmont alluvial plain, slopes westward onto a series of three pebble-covered raised sea beaches, called Tablazos, which constitute plateaus stepped up from sea-level to an elevation of 1,100 feet in the highest. Tertiary

rocks are exposed west of the mountains, where rapid erosion has cut through the breccia fan and tablazo deposits.

The Tertiary rocks are chiefly shales, with subordinate sandstones: the Zorritos formation, 5,000 feet thick and more, Miocene; the Lobitos formation, 5,000 feet plus, and the Negritos formation, 7,000 feet plus, both Eocene. They are of shallow-water origin, and their deposition, in view of their great thickness, was probably accomplished by subsidence of the sea bottom at intervals. These rocks are not folded; but close faulting has broken them into blocks, tilted in different directions, and at angles of 5° to 35°. This has been done by Andean upwarpings, in such a manner that this coast strip constitutes part of a "crush belt" along a geo-fault, the axis of which is believed to be in the Pacific Ocean at the edge of the continental shelf.

After this faulting there was a long period of erosion, with later submergence. In Quaternary times, a series of nearly vertical movements took place in which the Andes Mountains acted as a hinge, the free edge being the Pacific fault. There was a series of four episodes, beginning in each case with a marine transgression, the cutting of an extensive marine erosion plane, and the deposition of marine beds upon it; and terminating with an uplift, which elevated a plateau-like sea floor, or tablazo. The oldest and highest of these tablazos now stands at an elevation of 1,100 feet above tide, the ancient cliff line being only one or two miles from the foot of the Andes. The lowest and latest is now in the phase of emergence, giving partially flooded coastal plains.

The tablazo deposits consists of loosely compacted shell limestone, with large pebbles locally. This peculiar type of sediment is explained by the fact that no streams enter the ocean for 140 miles along the coast, except during the floods which occur twice or three times in a century; the accumulating calcareous material being free from clastics except at such times.

After the uplift of the first of these tablazos, exposing a large flat surface at the foot of the mountains, the floods from the latter aggraded great piedmont alluvial "breccia fans" on the tablazo; and the subsequent cutting back of streams into the latter gave terraces in the alluvium. With the development of the succeeding tablazos, similar aggradation and subsequent terrace cutting occurred in connection with each.

The author draws some interesting conclusions from his field observations as to the length of time, concluding that not one ten thousandth part of Quaternary history could have taken place within the last 500 years. This conclusion is based upon the hundreds of feet of observed

diastrophic movement in Quarternary time, the several retreats and advances of the sea, with the cutting of cliffs ten to twenty miles inland each time; the deposition of hundreds of feet of limestone between uplifts; the carving of deep valleys in the terraces back from the sea; and the fact that while the cycle of coastal movements is still in operation the amount of movement has been imperceptible in historic times (since the time of the Incas).

He points out peculiar conditions and processes in the desert at the present time. The work of the sun, slicing the pebbles of the alluvial deposits into thin angular fragments, is shown. The facetting of pebbles by the wind is a common feature, and is carried to the point where, of the original pebbles, small splinter-like fragments alone remain. A type of stream-lined topography developed by the wind is described. A discussion is given of the sand dunes of the area, in which he presents instructive observations and ideas, stressing the location and shape of dunes as influenced by their function as a filler for dead air space. The discussion of crescentic dunes is of particular interest.

A section on the Paleontology of the Tertiary formations by Messrs. Woods, Vaughan, Cushman, and Hawkins is the only part of the volume not contributed by the principal author. The Negritos fauna is correlated with that of the Wilcox and Lower Claiborne groups of the Gulf Coast Eocene; and is also stated to resemble Alpine, French, and English Eocene faunas, pointing somewhat to an Eocene trans-Atlantic ocean, with northern and southern shore-lines. The Lobitos fauna is called upper Eocene, in part at least. A number of excellent plates illustrate the detailed description of the different species.

The section on the petroleum geology stresses the lack of anticlinal structure, and the absence of oil except in the Tertiary. Surface indications of oil are abundant, such as oil seeps; oil-bearing mud volcanos; petroleum odor, of sandstones particularly; and the presence of petroleum on the sea near by. A large part of the total Tertiary section is productive at one horizon or another, although few of the sands are continously traceable laterally. Their productivity is highly variable, probably because of the extensive faulting; resulting in moderate sized wells over a large area. There is little or no underground water.

The character of the oil, which is dark to greenish brown, mixed base, and chiefly from .81 to .85 specific gravity (43.2–35 Be), changes near the old shore-line at the foot of the Andes, where it becomes heavier and more asphaltic. In general the oil gives 15–35 per cent of distillate at 150° C.; 30–50 per cent at 150–300°, and good lubricants from the

remainder, the lubricants from some of the oils showing a notably low solidifying point.

The most important fields are the Zorritos, Lobitos, Negritos, Cabo Blanco, and Lagunitas. The district described produces more than 99 per cent of the total Peruvian output, and about .5 per cent of the world's annual supply. Seventy-five per cent of the product is controlled by the International Petroleum Company of Toronto (an Imperial Oil Company subsidiary), and about $22\frac{1}{4}$ per cent by a British company (Lobitos Oilfields, Ltd.).

The reviewer found the volume enjoyable to read because of its large print and abundance of headings, as well as the good diagrams, maps, and illustrations. There is not a little repetition of the subject-matter, not all of which seems unavoidable, or desirable for clarity; but the book is highly interesting and instructive, both for the general geology of this unusual region, and the petroleum geology of the important oil occurrence.

T. B. R.

Untersuchungen uber die Tektonik der Lessinischen Alpen und über die Verwendung statistischer Methoden in der Tektonik, I. Teil. By J. Pia. Denkschriften des Naturhistorischen Museums in Wien. Band 2. Geologisch-Palaeontologische Reihe 2. 1923. Pp. 229, pls. 5, figs. 61, tables 86. (Price $4.80. Orders to be addressed to Geologische Abteilung des Naturhistorischen Museums, Wien I. Burgring 7.)

The first chapters of this book are devoted to a detailed tectonic description of the mountains situated between the rivers Etsch and Brenta, from the Sugana Valley on the north to the plain of Venice on the south. The folds of this region are very slight in comparison with the rest of the Eastern Alps. They show more or less distinctly the character of knee-bends. They are crossed by a richly developed system of faults, mostly directed toward NNW. The description is illustrated by a table of sections and by a tectonic sketch-map.

The second part of the book is of more general importance. It deals with an attempt to adapt statistical methods to tectonic descriptions, which may enable us to describe in a more accurate way the direction and intensity of folding in different areas. The leading idea of the method described by Dr. Pia is to divide the compass-card into a limited number (16) of directions and to represent the sum of all the dips attribu-

table to each direction by a line of appropriate length directed in the same sense. By doing so one gets a drawing called a diagram by the author. The diagram enables us to find by graphical or—more accurately—by arithmetical methods, figures characterizing the state of folding with respect to its intensity, direction, and uniformity. There is also shown the possibility of calculating the exactness of those figures, so that the tectonics of different areas may be compared in the same way as the features of organisms are compared in biometry.

The mathematical methods used by the author are rather simple ones which may easily be understood and used by every field-geologist interested in this kind of research. On the other hand, a more exhaustive treatment of the mathematical problems connected with the matter seems to be indispensable for further progress. No attempt has yet been made to utilize this system in regions more intensely disturbed, such as those of truly alpine character. It may be doubted whether it will be possible to do so.—*Author's Abstract.*

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Die Oberflächengestaltung des östlichen Suganer Gebietes (SO-Triol), von Robert Schwinner. Ostalpine Formenstudien, Abteilung 3, Heft 2. Mit 1 Abbildung und 2. Tafeln. Berlin: Verlag von Gebrüder Brontraeger, 1923.

The Geology of the Lower Findhorn and Lower Strath Nairn, including Part of the Black Isle near Fortrose. By John Horne. Memoirs of the Geological Survey, Scotland, 84 and part of 94. Edinburgh, 1923.

Amerika: Eine Uebersicht des Doppelkontinents. II Geographische Kulturkunde. Von Dr. Karl Sapper. Sammlung Göschen. Berlin und Leipzig: Walter de Gruyter u. Co., 1923.

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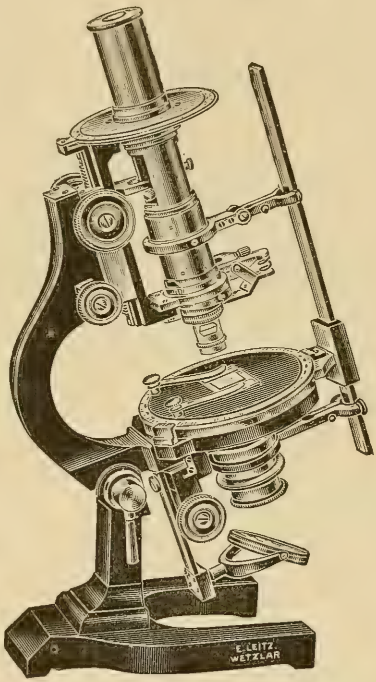

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THE PALEOZOIC ROCKS FOUND IN DEEP WELLS IN WISCONSIN AND NORTHERN ILLINOIS[1]

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Geological and Natural History Survey, Madison, Wisconsin

INTRODUCTION

The study of the Paleozoic formations penetrated by deep wells in Wisconsin and northern Illinois was begun by the writer in 1912, when the entire collection of samples of drill cuttings that had been collected from that area by the United States Geological Survey[2] was donated to the University of Wisconsin. Since that date the co-operation of many well drillers and engineers has enlarged the collection until it now includes over 8,000 specimens. Its study has been carried on in connection with work on the outcrops for the Wisconsin Geological and Natural History Survey, mainly under the direction of Dr. E. O. Ulrich, of the United States Geological Survey. In the last few years the State Survey has paid well drillers five cents for each sample with a minimum of $2.50 for each record; sample bags with attached labels are furnished. After study of the samples blue prints showing the geological section, casing log, water levels, yield, and other data are

[1] Published by permission of the state geologists of Illinois and Wisconsin.

[2] M. L. Fuller, E. F. Lines, and A. C. Veatch, "Record of Deep Well Drilling for 1904," *U.S. Geol. Survey Bull. 264* (1905), pp. 76–77. M. L. Fuller and Samuel Sanford, "Record of Deep Well Drillings for 1905," *U.S. Geol. Survey Bull. 298* (1906), pp. 176–79, 295–96.

furnished free to both owners and drillers. This policy, combined with visits to drillers in the field, has resulted in a constantly increasing percentage of good records of new wells.

The present paper is not intended to treat the subject of the paleontology nor to outline the history of the separation of the formations. For these subjects reference may be made to the works of Owen, Hall and Whitney, Wooster, Chamberlin, Strong, Irving, Hall and Sardeson, Sardeson, Ulrich, Walcott, Savage, Savage and Ross, Twenhofel and Thwaites, Alden, Bassler, and others.[1]

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The writer is greatly indebted to Dr. Ulrich for the inspiration which led to this study and for much unpublished information, and to Mr. F. W. DeWolf for opportunity to examine records from Illinois. The nomenclature and correlation of the formations here given is that proposed by Ulrich and the writer takes no responsibility for it as a number of features have not yet met with general acceptance.

"The Paleontology of the Niagaran Limestone in the Chicago Area: the Trilobita," *Chicago Acad. Sci. Nat. Hist. Survey Bull. 4*, 1907, Pt. 2, pp. 161–281; "The pre-Richmond Unconformity in the Mississippi Valley," *Jour. Geol.*, Vol. XV (1907), pp. 519–25. F. W. Sardeson, "The St. Peter Sandstone," *Minnesota Acad. Nat. Sci. Bull.*, Vol. IV (1910), pp. 64–88; "The Fauna of the Magnesian Series," *ibid.*, pp. 92–105. E. O. Ulrich, "Revision of the Paleozoic System," *Geol. Soc. Amer. Bull.*, Vol. XXII (1911), pp. 281–680. C. D. Walcott, "Cambrian Geology and Paleontology," *Smithsonian Misc. Coll.*, Vol. LII (1914), No. 13, p. 354 (gives section by Ulrich). G. H. Cox, "Lead and Zinc Deposits of Northwestern Illinois," *Illinois State Geol. Survey Bull. 21*, 1914. R. S. Bassler, "Bibliographic Index of American Ordovician and Silurian Fossils," *U.S. Nat. Museum Bull. 92*, 1915, Plates 2 and 3. G. H. Cady, "The Structure of the La Salle Anticline," *Illinois State Geol. Survey Bull. 36*, (1916), pp. 105–41. T. E. Savage and C. S. Ross, "The Age of the Iron Ore in Eastern Wisconsin," *Amer. Jour. Sci.*, Vol. XLI (1916), pp. 187–93. E. O. Ulrich, "Correlation by Displacements of the Strand-Line and the Function and Proper Use of Fossils in Correlation," *Geol. Soc. Amer. Bull.*, Vol. XXVII (1916), pp. 459–61, 477–78. T. E. Savage, "Alexandrian Rocks of Northeastern Illinois and Eastern Wisconsin," *ibid.*, pp. 305–24. G. H. Cady, "Geology of the La Salle and Hennepin Quadrangles," *Illinois State Geol. Survey Bull. 23*, (1917), pp. 55–65; "The New Richmond Sandstone of Northern Illinois" (abstract), *Illinois Acad. Sci. Trans.*, Vol. IX (1917), p. 210. W. C. Alden, "Quaternary Geology of Southeastern Wisconsin," *U.S. Geol. Survey Prof. Paper 106*, (1918), pp. 71–99. G. H. Cady, "Geology and Mineral Resources of the Hennepin and La Salle Quadrangles," *Illinois State Geol. Survey Bull. 37*, 1919. W. H. Twenhofel and F. T. Thwaites, "The Paleozoic Section of the Tomah and Sparta Quadrangles, Wisconsin," *Jour. Geol.*, Vol. XXVII (1919), pp. 614–33. E. O. Ulrich "Major Causes of Land and Sea Oscillations," *Washington Acad. Sci. Jour.*, Vol. X (1920), pp. 72, 77; *Smithsonian Report for 1920*, (1922), pp. 321–38.

Reference may also be made to the folios of the *Geologic Atlas of the United States*, Nos. 81, 140, 145, 200, and 201, and to publications dealing with Minnesota, Iowa, and northern Michigan; especially W. H. Norton *et al.*, "Underground Water Resources of Iowa," *U.S. Geol. Survey Water-Supply Paper 293*, 1912, and *Iowa Geol. Survey*, Vol. XXI, 1911; C. W. Hall *et al.*, "Geology and Underground Water of Southeastern Minnesota," *U.S. Geol. Survey Water-Supply Paper 256*, 1912; R. A. Smith, "Results of Deep Borings," *Michigan Geol. and Biol. Survey Pub. 24*, (1916), pp. 214–18, 238–39. A manuscript report on the Sparta and Tomah quadrangles, Wisconsin. is in the hands of the U.S. Survey, and Dr. Ulrich is preparing a report on the stratigraphy of Wisconsin.

THE PALEOZOIC SECTION (FIGS. 1 AND 2)

General.—The Paleozoic rocks of southern Wisconsin and northern Illinois comprise sediments of Cambrian, Ozarkian, Canadian, Ordovician, Silurian, and Devonian age. The Cambrian rocks are dominantly sandstones; higher in the column dolomite is more conspicuous. All the formations outcrop in Wisconsin, but in Illinois no Cambrian rocks appear at the surface. The tracing of individual formations from the outcrop to beneath cover has been done mainly by following certain markers or key-beds of well-defined lithologic character, rather than by counting down from the surface. For this purpose it was found desirable to construct sections where one horizon is drawn as a straight line, thus eliminating the confusing effect of structure. The sections herewith presented also show the sea level elevations of the wells. In the discussion of the several formations brief notes are given on their distribution and topographic expression. The data presented herewith are of a purely lithologic nature, the intention being to define the formations in such a manner that they can be distinguished by those not familiar with fossils and in wells where the finding of fossils is extremely uncommon.

Comparatively few of the Wisconsin well records based on samples have been published;[1] in Illinois the reverse is true.[2] The present paper does not aim to present the many well records in detail, but only the general results on which the correlations of the deeply buried strata are based.

DEVONIAN SYSTEM

MILWAUKEE FORMATION

Distribution.—The Milwaukee formation of Devonian age is known only near Milwaukee, Wisconsin, and in a few small adjacent areas. On account of the drift cover it shows no surface expression.

Character.—The Milwaukee formation is mainly dark gray dolomitic shale; there are some layers of gray shaly dolomite

[1] Samuel Weidman and A. R. Schultz, "The Underground and Surface Water Supplies of Wisconsin," *Wisconsin Geol. and Nat. Hist. Survey Bull. 35*, 1915.

[2] J. A. Udden, "Some Deep Borings in Illinois," *Illinois Geol. Survey Bull. 24*, 1914. C. B. Anderson, "The Artesian Waters of Northeastern Illinois," *Illinois Geol. Survey Bull. 34*, 1919.

which were formerly used for cement. The shale is called "soapstone," by local well drillers; it caves badly. The maximum known thickness is 168 feet at Milwaukee.

SILURIAN SYSTEM

Cayugan Series

General.—The Cayugan series is represented in Wisconsin by the very thin and discontinuous Waubakee dolomite which is found in spots along the Lake Michigan shore.

Niagaran Series

CLINTON AND LOCKPORT GROUPS

Distribution.—The Niagaran series of dolomites (Niagara formation of old reports) forms a conspicuous series of cuestas which extend south from the Door Peninsula in Wisconsin. South of Kewaunee County, Wisconsin, the minor escarpments which mark the different formations are covered by drift and south of Mayville, Wisconsin, the western edge of the belt is itself buried so deeply that the mapping of the Niagara area is based wholly on well records. In northwestern Illinois the Niagaran dolomites cap the higher hills, and a few scattered outliers are found in southwestern Wisconsin.

Character.—The Niagaran series of Wisconsin consists from the base up of the Mayville, Byron, Waukesha, Racine, and Guelph formations. The Waukesha of northeastern Wisconsin was called the Lower and Upper Coral beds in older literature. Ulrich places the Mayville in the Clinton group, and inasmuch as the Byron is poor in fossils, it is possible that the line of division might be drawn still higher. Ulrich has found a pre-Clinton dolomite (Burroughs dolomite) beneath the Niagaran in northwestern Illinois whose extent and character are but slightly known.

The Niagaran series is almost wholly light gray to pure white dolomite; locally pink, red, and less commonly, blue colors are met with in the lower portions. In southeastern Wisconsin and northeastern Illinois layers of blue, pink, and red calcareous shale are found near the base, notably at Milwaukee, Union Grove, and Racine, Wisconsin, and at Area, North Chicago, Maywood, and Elmhurst, Illinois. These basal rocks are probably older than the

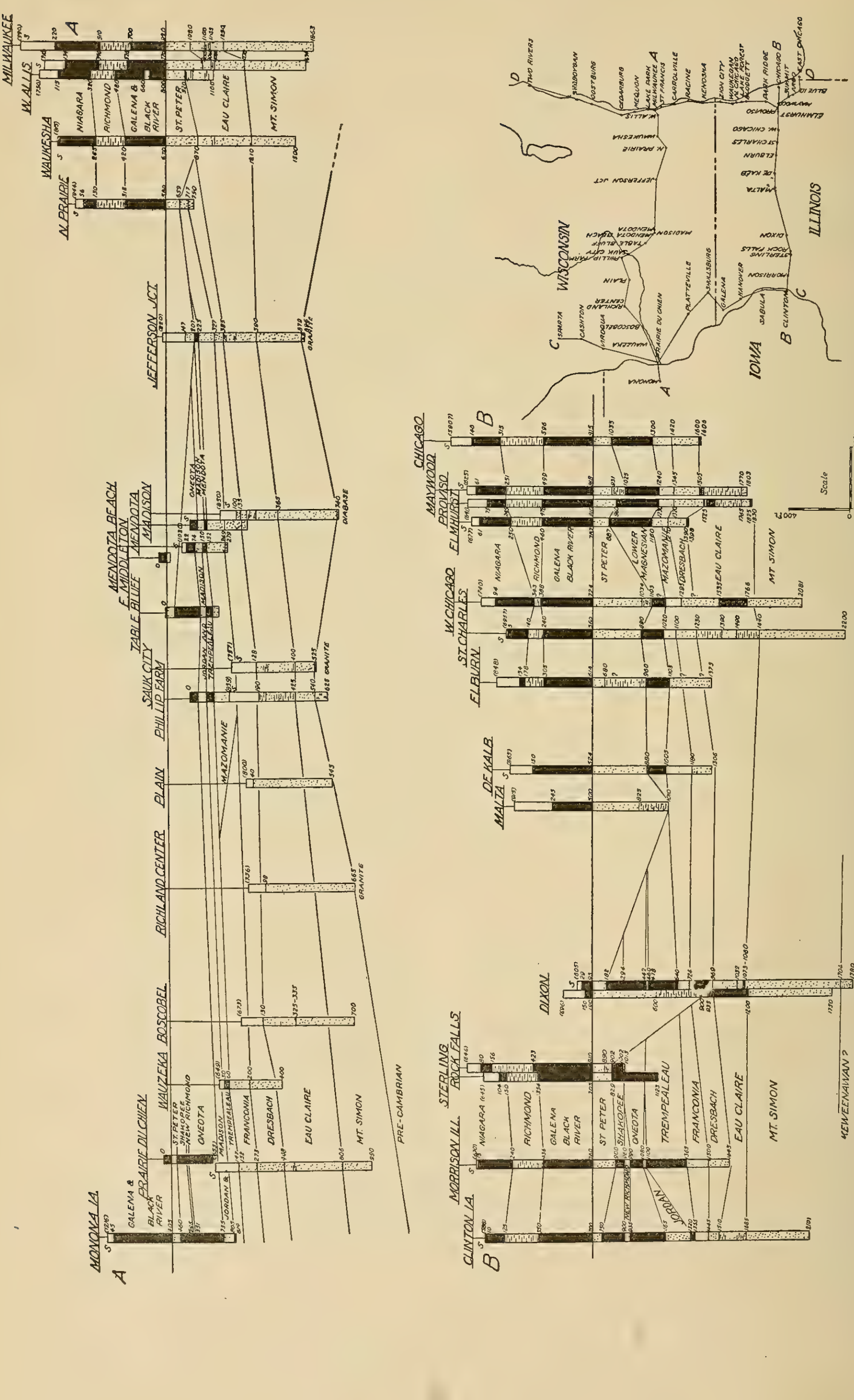

FIG. 1.—*A–A*. Section from Monona, Iowa, to Milwaukee, Wisconsin. *B–B*. Section from Clinton, Iowa, to Chicago, Illinois. Key map showing location of sections. These sections are drawn with the base of the Black River group as a horizontal line. Small figures at the right represent depths in feet; figures in parentheses represent sea level elevations of wells; *S* denotes record based on samples; *O* denotes outcrop. Drift is shown in white; limestone and dolomite in solid black; shale in broken lines; sandstone in dots; and sandy dolomite in black

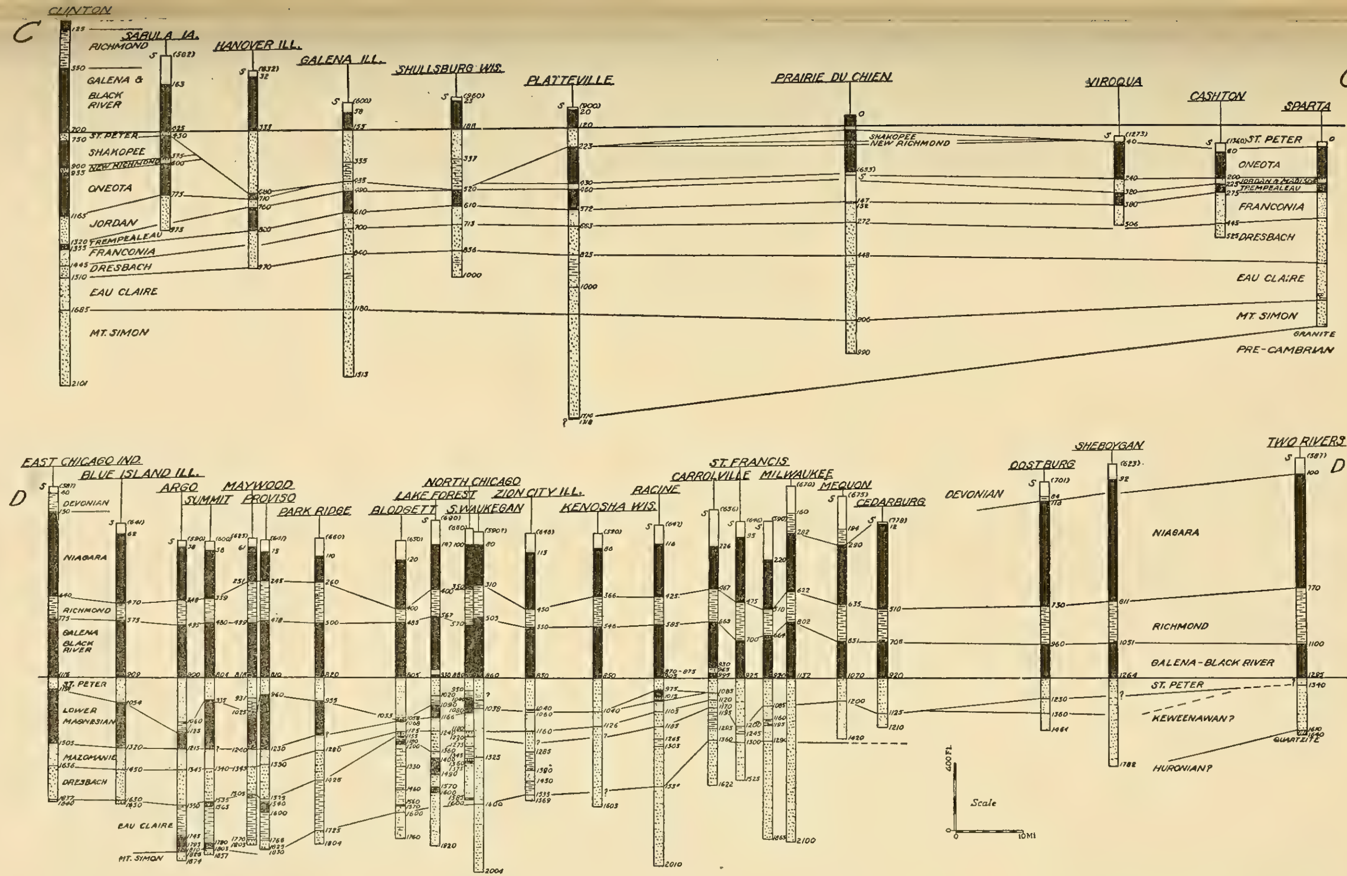

FIG. 2.—*C–C*. Section from Clinton, Iowa, to Sparta, Wisconsin. *D–D*. Section from East Chicago, Indiana, to Two Rivers, Wisconsin. These sections are drawn with the base of the Black River group as a horizontal line. Small figures at the right represent depths in feet; figures in parentheses represent sea level elevations of wells; *S* denotes record based on samples; *O* denotes outcrop. Drift is shown in white; limestone and dolomite in solid black; shale in broken lines; sandstone in dots; and sandy dolomite in black with white dots.

Mayville.[1] The bedding of the several formations varies from thin and regular in the Byron formation to massive in parts of the Waukesha and Racine formations. Indeed the separation of the formations in drill records is very difficult if no data on thickness of bedding are available. Chert of white and less commonly blue color is found in all the formations; it is most abundant in the basal Mayville and in the upper part of the Waukesha. The thickness of the whole Niagaran series varies from 300 to 670 feet increasing toward the northeast.

ORDOVICIAN SYSTEM[2]

MEDINAN SERIES

"CLINTON" OR NEDA FORMATION

General.—The "Clinton" or Neda formation occurs only in local lenses which outcrop in Dodge and Door counties, Wisconsin. These rise as mounds from the even surface of the Richmond. The Neda is found so rarely in deep wells that it requires no further discussion than to state that the deposits are oolitic hematite with subordinate red shale layers and shale pebbles.[3] The greatest known thickness is 55 feet at Manitowoc, Wisconsin.

RICHMOND GROUP

Distribution.—The Richmond group ("Cincinnati" or "Hudson River" formation of older reports) outcrops in a narrow belt along the Niagara escarpment in eastern Wisconsin and northeastern Illinois. In southwestern Wisconsin and northwestern Illinois there are many patches of Richmond beds, there called the Maquoketa shale.

Character.—The Richmond group in eastern Wisconsin consists mainly of dark blue calcareous shale, for the greater part very

[1] W. C. Alden, "The Quaternary Geology of Southeastern Wisconsin," *U.S. Geol. Survey Prof. Paper 106*, (1918), pp. 89–90. F. T. Thwaites, "Recent Discoveries of 'Clinton' Iron Ore in Eastern Wisconsin," *U.S. Geol. Survey Bull. 540*, (1913,) pp. 338–41.

[2] The Richmond group is placed in the Silurian by Ulrich, but all older writers and the majority of geologists at the present time place it in the Ordovician.

[3] The conclusions expressed by the writer in 1913 as to the feasibility of mining this ore under heavy cover need revision. There is now little question that the red beds near Kenosha are not iron ore, and that a fault occurs near Manitowoc; this would cause great difficulty with water at the latter locality.

soft, but in some layers of slate-like consistency. Interstratified with the shale at certain horizons are beds of gray and blue dolomite and magnesian limestone. In northeastern Wisconsin portions of the shale are brown-colored and, when heated, give off a strong oily odor. The correct interpretation of drill samples is hampered by the fact that some have been washed while others have not; the former give quite an erroneous impression of the character of the material.

In northeastern Wisconsin the following subdivisions of the Richmond group have been distinguished in wells: in ascending order (*a*) brown shale about 100 feet; (*b*) blue shale 58 to 105 feet; (*c*) brown shale, locally gray and slaty 5 to 62 feet; (*d*) blue shale 34 to 105 feet; (*e*) blue and gray dolomite interbedded with blue shale 35 to 70 feet; (*f*) blue shale 42 to 90 feet, and (*g*) gray, blue, and purple shaly dolomite with nodules of chert and gypsum 35 to 50 feet. Of the foregoing (*a*) is known only at Sturgeon Bay; (*e*), (*f*), (*g*), and possibly (*d*) are exposed at the surface; and (*c*) is quite irregular in distribution and thickness. The last is readily overlooked as the dried samples are hard to distinguish from the grayish blue shales above and below. The Niagaran dolomites bevel across the top of the group so that as one goes south along the shore of Lake Michigan, the younger series rests upon successively older and older members of the Richmond. Where the Mayville dolomite rests upon the dolomite member (*e*), the exact plane of contact is difficult to determine. Throughout this district the Richmond group varies from a thickness of about 200 feet near Milwaukee, to over 540 feet in southern Door County.

In northern Illinois the group is thinner and very variable, both in thickness and in lithological character. Calvin[1] describes a full section of the Maquoketa beds in Iowa as, ascending (*a*) Elgin shaly limestones (limestones, dolomites, and shaly limestones interstratified with blue calcareous shale) 70 feet; (*b*) Clermont shale (blue shale) 15 feet; (*c*) Fort Atkinson limestone (yellow cherty dolomite and limestone) 40 feet; (*d*) Brainard shales (blue shale with limestone beds at top and bottom) 120 feet. Savage[2]

[1] Samuel Calvin, "Geology of Winneshiek County," *Iowa Geol. Survey*, Vol. XVI (1906), pp. 94–109.

[2] T. E. Savage, "Geology of Jackson County," *Iowa Geol. Survey*, Vol. XVI (1906), pp. 597–609.

states that the distribution of these members is erratic and that those below the Brainard shales are missing in some counties. There also appears to be considerable irregularity at the top of the Maquoketa. Ulrich[1] divided the Richmond of Iowa into several formations: ascending (*a*) Dubuque dolomite, (*b*) Wykoff limestone, (*c*) Clermont shale, (*d*) Maquoketa shale, (*e*) Fort Atkinson limestone, (*f*) Brainard shale, and (*g*) unnamed dolomite. In later unpublished work the succession is given as (ascending) Dubuque dolomite, Elgin shale, Fort Atkinson limestone, and Brainard shales. Whatever may be the final disposition of these divisions as members or as separate formations, it is clear that the irregularity of sequence in the Richmond group is due to the disappearance of certain lithologic units, both at the base and the top of the group. Most well records in northern Illinois show only blue calcareous shale; some disclose limestone, or dolomite layers, at either the top or the bottom of the group.

Mohawkian Series

TRENTON AND BLACK RIVER GROUPS

Distribution.—The Trenton group of Wisconsin is called the Galena formation, and the underlying Black River group was incorrectly termed Trenton in older literature. The revision of the formation names within these groups has not yet been entirely completed for Wisconsin, and since the two groups constitute a lithologic unit of limestones and dolomites a detailed discussion of this subject would be of little value in this paper.

The Trenton and Black River groups (Galena-Trenton of older reports) cap a broad cuesta in eastern and southern Wisconsin, whose escarpment is well marked from Oconto southwest to Green Lake, and from Cross Plains west along the north side of Military Ridge to Mississippi River. The groups constitute the surface rock of most of the southern Driftless Area and of much of northwestern Illinois.

Character.—In southwestern Wisconsin and northwestern Illinois the Black River group consists in ascending order of the Platteville calcitic limestone and the Decorah shale and shaly limestone.

[1] E. O. Ulrich, "Revision of the Paleozoic Systems," *Geol. Soc. Amer. Bull.*, Vol. XXII (1911), pp. 281–680.

Passing to the east, dolomite becomes more and more abundant until near Beloit, Wisconsin, the entire group consists of buff and blue dolomite; Sardeson proposed the name Beloit for the eastern equivalent of the Decorah and Platteville formations. The Galena formation is everywhere a dolomite; it is rather coarse grained, gray at depth, and weathers to a yellow sandy consistency near the surface. At its base in southwestern Wisconsin Ulrich finds the Prosser formation of Minnesota.

In northeastern Wisconsin less is known of either group. The Galena is certainly present as a gray dolomite with some bluish gray shaly partings. On lithologic grounds the entire thickness of

TABLE I

PARTIAL LOG OF WATERWORKS WELL, CEDARBURG, WISCONSIN

	Thickness (Feet)	Depth (Feet)
Dolomite, gray	110	815
Dolomite, mixed gray and light blue	5	820
Dolomite, gray	10	830
Dolomite, mixed light blue and gray	35	865
Dolomite, gray	25	890
Dolomite, bluish gray and gray	15	905
Dolomite, gray	10	915
Dolomite, gray, sandy	5	920
Total thickness	215	....

dolomites of that district can be divided into two divisions; of these the upper is almost wholly gray and the lower is blue, mottled blue and gray, and gray only in a few thin beds. Partings of blue dolomitic shale are much more common throughout the lower division. The well log shown in Table I is typical of this formation in eastern Wisconsin.

Too little is known of the outcrops in this region to warrant the writer in attempting to correlate the succession found in wells with the section to the southwest. Chert is conspicuous on all weathered outcrops of both the Galena and Beloit formations but is seldom met with in drill cuttings from eastern Wisconsin and northeastern Illinois. The chert is gray or white at depth, although weathered specimens assume a yellow color. In much of eastern

Wisconsin fresh rock is found immediately below the drift, so that the characteristic weathered phases of the west are wanting. The base of the Black River is sandy in many localities, and along a belt which runs south from Milwaukee parallel with the Lake Michigan shore, there is a distinct bed of sandstone near the bottom of the group; this is known to well drillers as the "Trenton Stray Sand." It has a maximum known thickness of about 30 feet and consists of rather coarse-grained gray calcareous sandstone. This rock differs from the St. Peter in greater size of grain, lack of chert fragments, and in its dolomite cement which is locally sufficient to cause the rock to break in thin chips under the drill. The "stray sand" is confined, so far as known, to an area where the thickness of the Trenton and Black River groups is over 300 feet, although it is not present everywhere that the dolomites reach that thickness. It is probable that locally it lies directly upon the St. Peter, but where it can be distinguished with certainty, there are a few feet of more or less sandy dolomite between the two sandstones. There are some evidences that the "stray sand" is present elsewhere in Wisconsin. The thickness of the entire Trenton and Black River groups varies from 179 to 450 feet.

Big Buffalo Series

ST. PETER FORMATION

Distribution.—The St. Peter formation outcrops in the Galena–Black River escarpment, along valleys which cut the back slope of the cuesta, and in small inliers as far south as La Salle, Illinois. Being a soft formation it forms either steep slopes with occasional cliffs and crags, or low broken country with many small knolls. The extent in Illinois is greater than indicated on existing geological maps, for well records show it to lie immediately below the drift of valleys as far south as Rockford.

Character.—The St. Peter is dominantly a light gray or yellowish gray, fine to medium grained, more or less dolomitic sandstone; below the sandstone are beds of purplish red and green shale interstratified with layers of white disintegrated chert, and conglomerate with chert and limestone pebbles in a matrix of fine to coarse sand. These basal beds cave very badly in wells and must generally be cased off. At Shullsburg, Wisconsin; Galena, Illinois,

and elsewhere they are a very difficult horizon to penetrate with the drill. The caved material mixes with cuttings from lower horizons making some records very hard to interpret. The record is typical of the St. Peter where the basal beds are thick (Table II). The thickness of the St. Peter sandstone and underlying shales and conglomerate is known to reach at least 325 feet and may possibly exceed 600 feet in Illinois; in Wisconsin the maximum thus far

TABLE II

PARTIAL LOG OF WATERWORKS WELL, SHULLSBURG, WISCONSIN

	Thickness (Feet)	Depth (Feet)
Sandstone, coarse, gray, very calcareous; pyrite	5	193
Sandstone, medium to fine, light gray	77	270
Sandstone, medium to coarse, light gray	20	290
Sandstone, medium, light yellowish gray	35	325
Sandstone, medium, light pink	7	332
Sandstone, medium, light yellowish gray	15	347
Sandstone, medium to coarse, reddish gray; some red shale at top	18	365
Sandstone, medium, light yellowish gray	30	395
Sandstone, coarse, red; shale, red	2	397
Shale, dark red with greenish gray spots and pebbles of white chert	38	435
Conglomerate: pebbles white chert, matrix red shale	18	453
Shale, red with greenish gray spots and a few pebbles of white chert	5	458
Conglomerate like above	4	462
Shale, red and green mixed, pebbles of white chert and some sand	20	482
Sandstone, fine, gray, very calcareous; chert and red shale, caves badly, probably conglomerate	20	502
Sandstone, fine, gray, pink and green mixed; and red shale, caves badly, probably conglomerate	18	520
Total thickness	332	....

recorded in 332 feet, at Shullsburg. Its average thickness is very much less.

Sub-St. Peter unconformity.—Study of well records leaves no doubt that there is an unconformity of great magnitude at the base of the St. Peter. The shales at this horizon are virtually all non-calcareous and appear to be more or less deoxidized residium from the underlying dolomites. The chert beds and conglomerates represent assortment of residual deposits by water. The relief of the surface of the underlying dolomites is over 300 feet; places with no St. Peter sandstone occur within a few miles of localities

where there is no Lower Magnesian.[1] An example of this phenomenon occurs between Green Bay and De Pere, Wisconsin. Over an area of several thousand square miles in eastern Wisconsin and in portions of northern Illinois, the St. Peter rests upon the Cambrian; formations ranging from Jordan to Eau Claire have been distinguished at different places as underlying the St. Peter. The bottom of the St. Peter is best studied from well records, since the softness of the rocks causes this horizon to be concealed quite generally at the surface. At some exposures the beds of the underlying dolomite dip with the irregularity of the bottom of the sandstone; the writer is not prepared to state the significance of this phenomenon. Where the St. Peter rests upon the Cambrian sandstones, it is at places almost impossible to make out the exact plane of contact; such is the case near Milwaukee.

CANADIAN AND OZARKIAN SYSTEMS[2]

LOWER MAGNESIAN GROUP (PRAIRIE DU CHIEN FORMATION)

Distribution.—The Lower Magnesian group has been termed the Prairie du Chien formation in some reports; however, Ulrich urges that the old name be retained for the present. He divides the group in ascending order into the Oneota dolomite, the New Richmond sandstone, and the Shakopee dolomite; of these he places the first in his Ozarkian system and the others in his Canadian system. The group caps a broad, well defined cuesta whose U-shaped escarpment surrounds the central plain of Wisconsin. In Illinois only a few small inliers of the Shakopee are associated with the areas of exposed St. Peter sandstone.

Character.—The exact discrimination of the several formations of the Lower Magnesian group has thus far been made only in the outcrops of the western part of Wisconsin. These formations can be followed in well records for some distance into Iowa and Illinois. The two dolomites are rather similar in character, both are gray and carry gray, yellow, and pink chert, some of which is oolitic. The presence of oolitic chert is a certain marker of the Lower

[1] According to Ulrich all this is good evidence tending to establish this unconformity as marking the base of the Ordovician in the Mississippi Valley.

[2] These systems have been proposed by Ulrich and have not as yet been generally recognized; others place most of the formations concerned in the Ordovician.

Magnesian group since it has never been discovered in any of the adjacent dolomite formations. In places where the underlying or overlying sandstones are absent this criterion is almost indispensable. In northeastern Wisconsin there are pink shaly layers within the Lower Magnesian which can readily be confused with the

TABLE III

Partial Log of Well of Peshtigo Pulp and Paper Company, Peshtigo, Wisconsin

	Thickness (Feet)	Depth (Feet)
Dolomite, mixed gray and bluish gray	5	125
Dolomite, gray; oolitic chert, gray; specks of blue and green shale; caves	20	145
Dolomite, gray; shale, green; sandstone, gray	15	160
Dolomite, gray in part with floating sand grains; shale, blue; sandstone, fine, gray	15	175
Dolomite, gray; shale, blue; chert, pink	10	185
Sandstone, coarse to medium, light gray, calcareous	15	200
Sandstone, like above with layers of dark and light gray dolomite	5	205
Dolomite, dark and light gray, floating sand grains; layers of gray calcareous sandstone	5	210
Dolomite, dark and light gray layers	42	252
Dolomite, light gray; chert, oolitic, light gray	3	255
Dolomite, light gray; some sandstone, purplish, red, calcareous.	5	260
Dolomite, banded purplish red, gray, and green, shaly, sandy	5	265
Sandstone, coarse to medium, light pink, very calcareous	2	267
Dolomite, gray, green, and pink with layers of sandstone like above	8	275
Dolomite, light gray	10	285
Dolomite, gray with layers of sandstone and some oolitic chert	4	289
Dolomite, gray with much gray chert	4	293
Dolomite, gray with some chert	22	315
Dolomite, coarsely crystalline, gray	7	322
Dolomite, white and gray, chert, gray, both oolitic and dense	4	326
Dolomite, gray	41	367
Total thickness	247	....

underlying red beds of the Trempealeau. The writer has placed the bottom of the group at the lowest cherty gray dolomite.

Sandstone beds occur at several levels in the Lower Magnesian group and, except in northwestern Illinois and southwestern Wisconsin, have not been correlated with the formations described above. For the most part the sandstones are relatively coarse grained, light gray or white, and locally contain thin layers of dolomite and less frequently chert pebbles. A white sandstone

with abundant specks of green shale occurs near the base of the Oneota in western Wisconsin. In northeastern Wisconsin there are several "stray sands" some of which have doubtless been mistaken by well drillers for St. Peter. These sandstones are not good markers; closely spaced records in the Fox River Valley show that they pass horizontally within relatively short distances into floating sand grains in a dolomite matrix. The well record in Table III shows the character of the Lower Magnesian group in far northeastern Wisconsin. Not enough work has been done on the outcrops in this region to permit of correlating any of these beds with the western section.

The maximum known thickness of the Lower Magnesian group is over 700 feet in western Illinois; to the northeast it is much thinner, in many places less than 100 feet. Throughout several counties in eastern Wisconsin the dolomite is absent so far as known from well records; within this district its horizon is represented in some places by a thin layer of chert and non-calcareous clay, residium of the cherty dolomites, but near Milwaukee no trace of the Lower Magnesian has been found.

CAMBRIAN SYSTEM[1]

Madison Formation

Distribution.—The type locality of the Madison formation is the quarries just west of Madison. The formation, which lies immediately beneath the Oneota, has been traced in outcrops from that locality about 25 miles to the west. A few outcrops occur east of Madison, and it is also known in a well record at Sun Prairie, Wisconsin. Beds of somewhat similar character in the western part of Wisconsin are believed by Ulrich to represent the Madison.

Character.—The Madison of the original locality is a fine grained, buff, calcareous sandstone at the top, which passes below to a pure white medium grained sandstone much like the Jordan. In well samples it can only be distinguished from the Jordan, which underlies it throughout western Wisconsin, by its yellow color and dolomitic cement. The maximum thickness is about 50 feet.

[1] The Madison formation is regarded as the top of the Cambrian by most geologists; Ulrich places the top of that system at a lower horizon.

Mendota Formation

Distribution.—The Mendota dolomite as defined by Ulrich outcrops only in two small areas, one near Madison and the other near Baraboo, Wisconsin, where it caps small hills and terraces. It has not been definitely followed underground for more than a score of miles to the east of Madison, but may extend much farther.

Character.—The Mendota formation is a gray dolomite with purple and greenish gray blotches; glauconite is sparingly present and chert is nowhere found. In southeastern Wisconsin and northeastern Illinois there is a considerable thickness of chert-free, purple-spotted dolomite beneath the typical Oneota with its oolitic chert and green shale specks. If, as is known to be the case with the Jordan, the Madison loses its lithologic identity when followed down the dip from its outcrop, this rock may be in part at least of Mendota age.[1] The maximum proved thickness of the Mendota is about 20 feet, but if some of the non-cherty dolomite of Illinois is of the same age, the thickness may be several times as much.

[1] The stratigraphic position of the Mendota has caused more difficulty than any other problem within the area under discussion. Near Madison it is overlain by the Madison sandstone. Two or three feet of dolomite below the massive layers of the Mendota are regarded by Ulrich as the equivalent of the St. Lawrence or Black Earth dolomite member of the Trempealeau formation of western Wisconsin but contain no fossils. Under these layers is the Mazomanie sandstone with the same character, thickness, and with its top at exactly the same distance below the base of the Oneota as in the western section. At the west end of Lake Mendota we have in ascending order (*a*) Mazomanie sandstone, (*b*) red shale and glauconitic sandstone, (*c*) St. Lawrence or Black Earth dolomite member, (*d*) Lodi sandy dolomite member of Trempealeau formation, (*e*) Jordan sandstone, (*f*) Madison sandstone, and (*g*) Oneota dolomite. Two miles east we have a section so similar in lithologic character that were it not for the fossils described by Ulrich it would never have occurred to anyone to question its equivalence. The only difference is that (*d*) is thin or locally absent. According to Ulrich the testimony of the fossils places the Mendota dolomite of the south and east shores of Lake Mendota in his proposed Ozarkian system, in other words as younger than the Jordan sandstone. The fossils of the St. Lawrence or Black Earth member of the Trempealeau formation are strikingly similar to those of the Mendota although they show certain differences. The paleontological evidence is, therefore, at the present date entirely unsupported by stratigraphic data in this district. The exposures of Mendota dolomite near Baraboo do not show the same adjoining formations as at Madison; indeed the stratigraphic section close to the quartzite islands is in many respects quite different from elsewhere. It is therefore a question whether or not the Mendota of Baraboo is the same as the original Mendota dolomite at Madison; the correlation rests solely upon fossils. The entire question is fortunately of little importance in the study of well records since the Mendota is of very limited occurrence.

Devils Lake Formation

Distribution.—The Devils Lake formation is known only in a few exposures near the quartzite ranges at Baraboo, Wisconsin. It has never been located in a complete normal section away from the old beaches; indeed it is not positively known if all of the supposed occurrences are of the same age.

Character.—The Devils Lake formation consists of gray and yellow, more or less glauconitic sandstone and of quartzite pebble conglomerate. In the best known exposures, southwest of Baraboo, it is underlain by glauconitic sandstone and purple spotted dolomite unlike anything known in the normal section outside the quartzite ranges; at other places the formation has been found resting on the Jordan, and possibly on other formations. It is overlain in some places by the Mendota dolomite, and in others apparently by the Oneota dolomite. The formation in question is of no importance in the study of well records on account of its limited distribution; it is barely possible that some of the strata in southeastern Wisconsin here ascribed to the Mazomanie formation are Devils Lake. The thickness of the Devils Lake is not definitely known but may reach a maximum of over 100 feet.

CAMBRIAN SYSTEM[1]

Upper Cambrian Series (St. Croix Group)

JORDAN FORMATION

Distribution.—The Jordan sandstone outcrops in a narrow belt along the Lower Magnesian escarpment and in the sides of valleys within the cuesta as far east as near Cross Plains, Wisconsin; east of that point it has not been definitely distinguished. On the Mississippi it passes beneath the surface near Prairie du Chien, Wisconsin.

Character.—The Jordan sandstone is noted for its pure white color although in places some outcrops are yellow. The grain is fine to medium; calcite or dolomite concretions are abundant at the surface. Followed down the dip into northwestern Illinois the formation loses its identity as a lithologic unit and grades into sandy dolomite; no Jordan sandstone has been distinguished in

[1] As defined by Ulrich.

most of northeastern Wisconsin. The maximum thickness of the Jordan is about 75 feet; its lower limit is determined by the finer grain and more dolomitic character of the underlying Trempealeau.

TREMPEALEAU FORMATION

Distribution.—The Trempealeau formation has been called the St. Lawrence formation, and in older literature was correlated with the Mendota of the Madison region. The definition of this formation has varied from merely the thin "Black Earth" or original St. Lawrence dolomite bed, to all the strata between the base of the Jordan and the top of the Dresbach. In view of this conflict Ulrich has recently proposed a change in name.[1]

The Trempealeau formation caps narrow terraces just beneath the steep slopes of the Jordan outcrop. It is known throughout western Wisconsin and northwestern Illinois, but has not been definitely distinguished southeast of a northeast-southwest line through Madison.

Character.—The Trempealeau formation is divided by Ulrich into the following members from base up: (*a*) sandy dolomitic shales of local distribution, (*b*) St. Lawrence or Black Earth dolomite, a rock almost exactly like the Mendota, (*c*) Lodi yellow and purple sandy thin bedded dolomite, locally called "shale," and (*d*) Norwalk fine grained dolomitic sandstone. Of these the last is most conspicuous in western Wisconsin; along the Wisconsin River the Lodi "shales" predominate and farther south under cover there is less sand and (*b*) seems to make up the bulk of the formation. The yellow color does not persist in depth but is replaced by gray; this is not true of the purple tints. The base of the formation is marked by a greensand conglomerate; glauconite is only sparingly present at higher horizons.

The red and purple dolomites, for the most part quite sandy, that underlie the cherty gray Oneota in northeastern Wisconsin have been correlated by the writer with the Trempealeau formation; they are in few places separated from the younger dolomite by a sandstone. In western Wisconsin, however, the Trempealeau is overlain by the Jordan sandstone.

[1] At the date of writing the name Trempealeau has not been approved by the Board of Geologic Names of the U.S. Geological Survey.

The thickness of the Trempealeau formation is at a minimum of 35 feet in northeastern Wisconsin; in the southwestern district it exceeds 100 feet. The record shown in Table IV is typical of northeastern Wisconsin.

TABLE IV

PARTIAL LOG OF STATE REFORMATORY WELL, GREEN BAY, WISCONSIN

	Thickness (Feet)	Depth (Feet)
Dolomite, gray, sandy; layers of sandstone, fine, pink, hard, calcareous..........	15	470
Sandstone, fine to very fine, gray, pink, very calcareous, hard...	15	485
Sandstone like above but in part red and glauconitic..........	5	490
Total thickness..........	35	....

MAZOMANIE FORMATION

Distribution.—The Mazomanie sandstone is known from far northeastern Wisconsin to near Spring Green, Wisconsin. It is a rather firm rock and forms conspicuous crags among which may be mentioned the Natural Bridge, west of Prairie du Sac. A line drawn from Spring Green east of north through central Adams County separates the Mazomanie from the Franconia. The Mazomanie thins out to the west and overlaps the older Franconia for distances of 10 to 20 miles. Good examples of Mazomanie overlying Franconia can be found near Reedsburg and Friendship.

Character.—The Mazomanie consists of fine to medium grained gray to dark red sandstone, irregularly cemented by dolomite; locally there are beds of red, green, and gray calcareous shale. At depth some layers are so well cemented that they break into chips under the drill and are hence reported as limestone in drillers' logs, or described as sandy dolomite by some geologists who have examined samples. At Markesan and Green Lake, Wisconsin, the base of the Mazomanie consists of gray dolomite with purple spots, very similar to the St. Lawrence member of the Trempealeau. The red colors are of local distribution; they are mainly found in northeastern Illinois. The entire formation contains more or less glauconite and that mineral is most abundant near the top. This fact makes the Mazomanie a valuable marker in the geological column. The record is typical of the Mazomanie of eastern

Wisconsin and northeastern Illinois (Table V). In northern Illinois it was formerly correlated with the Madison and Mendota of

TABLE V

Partial Log of City Well No. 4, Kaukauna, Wisconsin

	Thicknes (Feet)	Depth (Feet)
Sandstone, very fine, pink and brownish red, very calcareous, glauconitic; seams of green shale	35	415
Sandstone, fine, mixed greenish gray and red, calcareous, glauconitic	15	430
Sandstone, coarse to fine, pinkish gray, hard, very calcareous	5	435
Sandstone, coarse to medium, white	20	455
Sandstone, medium to coarse, white, part pink and gray, calcareous	5	460
Sandstone, medium to coarse, white	25	485
Sandstone, medium to fine, white, hard, calcareous	10	495
Sandstone, very fine, gray, calcareous; shale, gray	5	500
Shale, gray, calcareous	5	505
Sandstone, fine, gray, calcareous; shale, gray, calcareous	5	510
Total thickness	130	....

Wisconsin, but bears no resemblance to those formations.[1] The thickness averages close to 100 feet with a maximum of 165 feet.

FRANCONIA FORMATION

Distribution.—The Franconia sandstone caps a wide cuesta in western Wisconsin which extends southeast from St. Croix Falls to near Baraboo. It also forms a bench along the valley sides within the Lower Magnesian cuesta. The surface of the formation is divided into several minor terraces each corresponding to some difference in relative resistance to weathering.

Character.—The Franconia sandstone is fine grained, gray to green in color, and for the most part somewhat calcareous. However, the lithologic character of the formation varies considerably in different parts of the state, and there are rapid changes in the character of the formation. For instance the yellowish sandstone of the Sparta district is represented near Viroqua at the same stratigraphic level by dark green clay shale. The greater part of the Franconia is highly glauconitic, especially near the bottom and

[1] C. B. Anderson, "The Artesian Waters of Northeastern Illinois," *Illinois State Geol. Survey Bull. 34* (1919), pp. 84, 107.

top. Near the base, particularly in the southwestern quarter of the state, is about 15 feet of micaceous sandy shale; this horizon is very important in wells since under ridges the water is held above it causing a spring line around the sides of bluffs. If wells go through the shale, the water level drops very markedly. Below the shale are a few feet of hard calcareous coarse-grained sandstone, the Ironton member. The thickness of the Franconia varies from 90 to 175 feet.

DRESBACH FORMATION

Distribution.—The Dresbach sandstone forms the cliffs of the Franconia escarpment in western Wisconsin. It is prominent in the numerous fantastic towers and buttes of the central part of the state. In the valleys within the Lower Magnesian cuesta, it outcrops in cliffs along the streams as far south as near Lone Rock on Wisconsin River. The white cliffs west of Prairie du Sac are Dresbach.

Character.—The Dresbach consists of medium-grained pure white sandstone with some yellow layers. The cement is mainly silica and varies greatly in amount; locally the formation is quartzitic. The upper and lower contacts are difficult to make out in some well sections. The writer has excluded from the formation all fine-grained, calcareous, or glauconitic sandstones. In central and northeastern Wisconsin the base cannot be determined, since the only change is in thickness of bedding. Not counting this district, the thickness varies from 40 feet at Union Grove, Wisconsin, to 180 feet at Chicago. In consequence of the high porosity and great purity of the formation it yields excellent water.

The Dresbach sandstone of Illinois was formerly correlated with the Jordan,[1] but the writer is convinced that this was an error because of the similarity of the succession of formations in deep wells to that found in outcrops near Sauk City, Wisconsin, and by the fact that the underlying formations are totally unlike any known Trempealeau, Franconia, or Mazomanie. The white sandstone formation has been followed through in well sections

[1] C. B. Anderson, "The Artesian Waters of Northeastern Illinois," *Illinois State Geol. Survey Bull. 34,* (1919), pp. 84, 107, Pl. II.

across Illinois to the outcrops near Prairie du Chien and La Crosse, Wisconsin, as well as directly northwest to Sauk City, Wisconsin.

EAU CLAIRE FORMATION

Distribution.—The Eau Claire formation underlies a large part of the lowlands of central Wisconsin. It forms flat-topped terraces and rolling country of low relief, only occasionally making a steep escarpment like that of the Dresbach. The formation outcrops along Mississippi River as far south as La Crosse. The thin bedded, cross bedded rock in the Dells of the Wisconsin is believed to belong to the Eau Claire.

Character.—The Eau Claire formation consists of sandstone and shale whose relative proportions differ greatly according to locality. In northeastern Wisconsin both outcrops and well records show clearly that the entire formation is sandstone of medium to fine grain, indistinguishable except by its thin bedding from either the overlying or underlying formations. In western Wisconsin, where the Eau Claire was first studied, the upper and lower parts are filled with thin seams and small lenses of greenish or bluish gray shale and most of the sandstone is very fine grained. There is some glauconite but not so much as in the younger Franconia; linguloid shells are locally prominent. The formation with increasing percentage of shale has been followed south in well records into northern Illinois. The section in that region bears so close a resemblance to that near Chicago that there can be no reasonable doubt that the shales below the white sandstone (Dresbach) of the east part of Illinois are the Eau Claire. A three-part subdivision is persistent; west of Chicago a fine-grained calcareous sandstone separates two members of gray and red calcareous shale or marl with some dolomite beds. On the whole, however, the Eau Claire is marked by extreme variability in character. Scarcely any two wells record exactly the same succession in detail; beds of gray marl, red marl, fine, medium, or rarely coarse-grained sandstone of pink, gray, or white colors alternate with very calcareous sandstones and in places pure dolomites, but in almost every case some vestige of the tripartate subdivision can be made out. Dolomite beds are commonest near the bottom and the top of the formation.

The records as shown in Tables VI and VII illustrate the variable character of the Eau Claire of the southeastern part of the area

TABLE VI

PARTIAL LOG OF ABBOTT LABORATORIES WELL, NORTH CHICAGO, ILLINOIS

	Thickness (Feet)	Depth (Feet)
Sandstone, very fine, gray, shaly, calcareous, slightly glauconitic; pyrite	30	1,250
Sandstone, fine to very fine, gray, calcareous	10	1,260
Shale, red, calcareous	15	1,275
Shale, gray, calcareous	35	1,310
Shale, mixed red and gray, calcareous	20	1,330
Shale, gray, calcareous	15	1,345
Sandstone, very fine, gray, calcareous	15	1,360
Dolomite, light gray	15	1,375
Sandstone, fine, gray, calcareous	125	1,500
Sandstone, very fine, gray, calcareous	35	1,535
Sandstone, very fine, gray, hard, very calcareous	25	1,560
Sandstone, exceedingly fine, gray, calcareous	10	1,570
Sandstone, fine, gray, calcareous	15	1,585
Dolomite, gray to bottom of well	15	1,600
Total thickness over	380	....

TABLE VII

PARTIAL LOG OF WELL AT SOUTHERN WISCONSIN HOME FOR THE FEEBLE-MINDED AND THE EPILEPTIC, UNION GROVE, WISCONSIN

	Thickness (Feet)	Depth (Feet)
Sandstone, very fine, brownish gray, calcareous	75	1,040
Sandstone, very fine, dark red, very calcareous, glauconitic	30	1,070
Shale, red with some gray beds, very calcareous	50	1,120
Sandstone, medium to very fine, pink, calcareous	20	1,140
Sandstone, medium to fine, light pinkish gray, calcareous	25	1,165
Sandstone, fine, gray, calcareous, coarser toward base	30	1,195
Sandstone, fine, gray, calcareous	30	1,225
Sandstone, medium to fine, dark gray, calcareous	15	1,240
Sandstone, fine, yellowish gray, calcareous	10	1,250
Sandstone, fine, gray, slightly calcareous	15	1,265
Sandstone, fine, white	10	1,275
Sandstone, fine to shaly, red, very calcareous	5	1,280
Sandstone, exceedingly fine, yellowish gray, calcareous	5	1,285
Shale, red, calcareous	5	1,290
Sandstone, medium to fine, pinkish gray, calcareous	45	1,335
Sandstone, medium to fine, gray, calcareous	20	1,355
Sandstone, very fine, pinkish gray, calcareous	5	1,360
Total thickness	395	....

under discussion; it is here much more shaly and dolomitic than nearer the outcrop.

In the region around Milwaukee the greatest difficulty was experienced in correlating the "red marl zone" as it is known to well drillers. The gray shales are almost entirely lacking in that district and the red layers are so erratic in both vertical and horizontal distribution that at first the problem seemed hopeless. The red marl at Milwaukee was formerly believed to be part of the Lower Magnesian.[1] However, by means of sections parallel to the lake shore it was determined that the red marls pass below the Dresbach sandstone of Illinois, and grade laterally into the gray and red marls of the Chicago district. This conclusion was verified by fossils which were shot out of a well at Waukesha and determined by Dr. Ulrich.

The thickness of the Eau Claire, as it can be distinguished in well records, varies from 70 feet at Rockford, Illinois, to 410 feet at St. Charles, Illinois; the average is not far from 350 feet.

MT. SIMON FORMATION

Distribution.—Outcrops of the Mt. Simon sandstone have thus far been studied only near Eau Claire, Wisconsin, its type locality. At that place it forms an escarpment which is capped by Eau Claire shaly sandstone. The Mt. Simon must be the basal member of the Cambrian over a wide area of drift-covered country in central Wisconsin.

Character.—The upper limit of the Mt. Simon sandstone is difficult to determine on account of the variable character of the overlying Eau Claire. In central Wisconsin the formation is mainly coarse to medium grained, gray or yellow sandstone with a few layers of green, blue, and red shale. Farther south less of the formation is coarse grained; locally there are pink layers, the color being deepest in the finer-grained sands. The record (Table VIII) is a fair example of the Mt. Simon rather close to the outcrop where there are more beds of coarse grain than farther south. The greatest recorded thickness is 778 feet at Platteville, Wisconsin.

[1] W. C. Alden, "Geol. Atlas of U.S.," *Milwaukee Folio No. 140*, (1906), p. 1; "The Quaternary Geology of Southeastern Wisconsin," *U.S. Geol. Survey Prof. Paper 106*, (1918), pp. 78–82. Samuel Weidman and A. R. Schultz, "The Underground and Surface Water Supplies of Wisconsin," *Wisconsin Geol. and Nat. Hist. Survey Bull. 35*, (1915), p. 457.

PRE-CAMBRIAN SYSTEMS

Base of the Paleozoic rocks.—The Paleozoic series rests upon a rather irregular basement of pre-Cambrian igneous and metamorphic rocks. Older attempts[1] to map this surface have not shown nearly as many buried monadnocks as are now known. For the most part these are composed of Huronian quartzite, not unlike that exposed at the surface near Baraboo and Waterloo, Wisconsin. At a number of places in Wisconsin these buried mountains rise high enough to cut off part or all of the water-bearing strata; such is the case at Hartford, Kewaskum, Two Rivers, and in part of Fond du Lac.

TABLE VIII

PARTIAL LOG OF CITY WELL NO. 11, MADISON, WISCONSIN

	Thickness (Feet)	Depth (Feet)
Sandstone, medium to fine, white	25	390
Sandstone, medium to fine, white; some beds hard, calcareous, pink	60	450
Sandstone, medium to fine, light gray	25	475
Sandstone, coarse to medium, light gray	45	520
Sandstone like above with layers of sandstone, fine, pink and green, hard, calcareous	10	530
Sandstone, coarse to fine, light gray	10	540
Sandstone, coarse to medium, light gray; layers of sandstone, fine, pink and green, hard, calcareous	20	560
Sandstone, coarse to fine, gray	35	595
Sandstone, coarse, gray; pyrite	10	605
Sandstone, very fine to medium, gray, shaly, non-calcareous	2	607
Sandstone, coarse to fine, gray, some layers pink	3	610
Sandstone, very coarse to fine, gray	20	630
Sandstone, medium to fine, gray	15	645
Sandstone, medium to fine, pinkish gray	5	650
Sandstone, fine, gray, shaly	30	680
Sandstone, very coarse to fine, pink	5	685
Sandstone, coarse to fine, gray	5	690
Shale, dark pink	5	695
Sandstone, very fine, pink	20	715
Sandstone, coarse to fine, gray	5	720
Shale, pink and red to pre-Cambrian	13	733
Total thickness	368	....

Possible Keweenawan sandstone.—No igneous or metamorphic rocks have ever been reached in northern Illinois, or on the Lake

[1] I. A. Lapham, Geological map of Wisconsin, 1869. Samuel Weidman and A. R. Schultz, *op. cit.*, map.

Michigan shore as far north as Sheboygan, Wisconsin. Deep wells in this belt are reported to find a red sandstone below the light-colored Cambrian, suggesting that possibly a Keweenawan sandstone fills the Michigan trough as one does the Lake Superior syncline. It is well established that the Keweenawan red sandstones of Lake Superior extend southwest into Minnesota below the Cambrian.[1] Few samples have been obtained from these rocks since, on account of the poor water which they yield, wells are no longer drilled deep enough to reach them.

[1] C. W. Hall, O. E. Meinzer, and M. L. Fuller, "Geology and Underground Waters of Southeastern Minnesota," *U.S. Geol. Survey Water Supply Paper 256*, (1911), pp. 32, 48. F. T. Thwaites, "Sandstones of the Wisconsin Coast of Lake Superior," *Wisconsin Geol. and Nat. Hist. Survey Bull. 25*, (1912), pp. 58–61.

THE STRUCTURAL GEOLOGY OF BRITISH MALAYA

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In the *Geographical Review* for July, 1921,[1] I published a short paper on the physical geography of the southern part of the Malay Peninsula, which is almost the same as "British Malaya": it has been suggested that a paper on the structural geology of the same country would be of interest. This paper therefore is an attempt to give a brief outline of the geological structure of British Malaya, an attempt which is now possible, though the detailed geological survey of every state has not been completed.

The table on page 557 is a statement of the geological sequence in so far as it is known at present, beginning with the youngest rocks:

Most of these rocks, if not all, have their counterpart in the Dutch East Indies. The granite and associated igneous rocks extend to them where a similar view is now held of the date of intrusion, i.e., the late Mesozioc. The three small patches of Tertiary rocks are but outliers of a great development of similar rocks in Sumatra. Both the younger volcanic rocks (Group 4) and the Pahang Volcanic Series are represented also in Sumatra, as also are the quartzites and shales and the calcareous group.

The Malay Peninsula belongs to a region of strongly marked coulisses[2] that sweep boldly round through the Malay Archipelago in a north easterly direction, on to the Philippines. They are arcs formed at the close of the Mesozoic Era.[3] This wrinkling of the earth's crust permitted the intrusion of large masses of plutonic

[1] *Geographical Review* (New York), Vol. XI (1921), pp. 351–71.

[2] This word "coulisse," used by Suess in his *Face of the Earth* and now by some Dutch geologists in the Malay Archipelago, is applicable to the Malay Peninsula because there the structural features are distinctly "*en échelon*" like the wings of a theatrical stage. But for this arrangement, the term "arc" is preferable as being more familiar. "Coulisse" figures in French and English dictionaries, but is not in common use, even among geologists.

[3] See Professor W. H. Hobbs, *Earth Evolution and Its Facial Expression*, p. 147.

1. Recent alluvium; particularly extensive on both the coasts of the Peninsula.
2. High-level alluvium; in Singapore, Johore, and perhaps in the Kinta District of Perak; raised beaches in several localities may be tabulated in this group.
3. Tertiary bedded rocks, probably Miocene, with coal. Only three small patches of these rocks are known.
4. Dolerite, rhyolite, and quartz-porphyry; extensive outcrops on the coast of Pahang and Johore. The dolerite, and in one case quartz-porphyry, is certainly younger than the granite. There is some doubt about the age of the rhyolite.
5. Granite, hornblende-granite, syenite, and small exposures of gabbro and norite. Small exposures of diorite may belong to this group also.
6. Extensive quartzites and shales in which two definite horizons have been found. In Perak and Kedah shales contain Triassic fossils; in Pahang and Singapore fine-grained sandy beds have yielded a Rhaetic fauna (Myophoria Sandstone). In Singapore Upper Gondwana plant-remains have been found with marine mollusca first described as probably on the horizon of the Inferior Oolite.[1] In the Kinta District of Perak, clays with boulders may be tabulated here. Chert pebbles are common in the coarser quartzites.
7. Quartzite with interbedded radiolarian chert, occurring in Negri Sembilan and believed to be the lowest part of the quartzite and shale series.
8. Chert and shales; extensive in Kedah and Pahang, and occurring elsewhere. They mark the beginning of the shallow water conditions under which groups 6 and 7 were deposited. In Perlis poorly preserved *Fusulinidae* have been found in chert, but this may be silicified limestone not belonging to this group.
9. Extensive calcareous shales and limestone with some non-calcareous beds. The limestone has yielded a definite Viséan fauna[2] in the Kuantan District of Pahang, and Carboniferous fossils elsewhere.

} A contemporaneous series of volcanic and hypabyssal rocks called the Pahang Volcanic Series. Exposures are extensive in Pahang and Kelantan. The series ranges from rhyolites to dolerites. Agglomerates and tuffs are particularly widespread.

10. Quartzite and shale with limestone bands overlain comformably by 9 in the Langkawi Islands. It is probable that rocks in Patalung (Lower Siam) with fossils belong to this group. The fossils were first described as Permo-carboniferous,[3] but have been re-examined and determined as probably Lower Carboniferous.[4]

[1] The fossils found in Singapore have been described by Mr. R. B. Newton who is now preparing a new paper on the subject.

[2] Described by Dr. Stanley Smith; his report has been published only in Malaya.

[3] Professor McKenny Hughes, *Rep. Brit. Assoc.*, Glasgow, 1901, p. 414.

[4] F. R. Cowper Read, *Geol. Mag.*, 1920, pp. 113–20 and 172–78.

rocks; in British Malaya these are chiefly granite, which yields the wealth of tin-ore with which the country is endowed.

Figure 1 is a sketch-map showing the coulisses in the Malay Peninsula and their probable connection with coulisses in the Malay Archipelago. The latter coulisses are taken from a paper by Van Es.[1] The dotted line shows the sweep of the arc as given in Figure 72 on page 147 of Professor Hobbs' work. My sketch-map shows that this arc is really a band in which are many small folds.

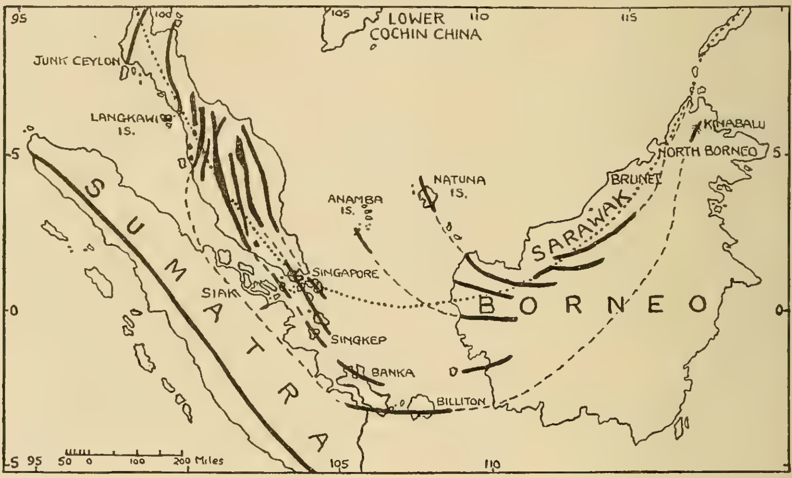

FIG. 1.—Sketch-map showing coulisses in the Malay Peninsula and Archipelago. The dotted line is the Peninsular-Bornean arc as shown in Fig. 72, p. 147, of Professor W. H. Hobbs' *Earth Evolution and Its Facial Expression.* The sketch-map shows that the arc is really a band containing many small folds.

Figure 2 shows in some detail the coulisses in British Malaya. The basis of the structure of the country may be described as a number of granite ribs or ridges occupying anticlines or more complicated folds in the older rocks, and connected in depth with a granite bathylith. These granite ribs, it may be argued, are in themselves so substantial as to merit the name of bathyliths, but their elongated form and small lateral extent make me think the term inapplicable.

[1] L. J. C. Van Es, "De tektoniek van de westelijke helft van den Oost-Indischen Archipel," *Jaarboek van het Mijnwezen in Nederl. Oost-Indië,* Vol. XLVI, Part II (1917), pp. 5–143.

FIG. 2.—Sketch-map showing the coulisses of British Malaya. The crosses indicate granite. 1. The Nakawn Coulisse. 2. The Kedah-Singgora Coulisse. 3. Gunong Perak. 4. Kedah Peak. 5. Penang. 6. Province Wellesley hills. 7. The Bintang Coulisse. 8. The Kledang Coulisse. 9. The Kerbau Coulisse. 10. The Benom Coulisse. 11. Mount Ophir. 12 and 13. The Tahan Coulisse, continued in Singapore. 14, 15, 16. The East Coast Coulisse.

The line from 3 to 10 joins the highest points of the granite ridges in each coulisse that it touches. Along this line from 3 to 9 there is a continuous granite outcrop, which is the roof of the bathylith that forms the foundation of the granite ribs, or coulisses of the Peninsula. In other parts of the Peninsula the country between the coulisses is composed of bedded rocks, shale and quartzite, or calcareous rocks, except for occasional small outcrops of granite, dolerite, rhyolite, and the Pahang Volcanic Series.

The form of the folding that led to the formation of the granite ribs cannot yet be said to be fully elucidated. The strata older than the granite are everywhere much disturbed. In the least disturbed area, the center of Pahang, the rocks are thrown into fairly sharp anticlines and synclines: in other areas they are squeezed together, pressed into a vertical position, contorted, and faulted. There is reason to suppose that the granite invaded a number of shattered anticlinoria, but in two localities there is some evidence of overfolding, with the pressure exerted from the WSW. One of these localities is in the Kinta District of Perak.[1] Here the Carboniferous limestone shows signs of great disturbance. Near Ipoh are pinnacles showing excellent examples of fault-breccias; in one crinoid-stems have been drawn out into threads in a thrust-plane. But not far distant from these pinnacles is a cliff-section which shows evidence of an overfold. The other locality is the western slope of the Tahan Range in Pahang, where the dips show a probability of similar overfolding, but the evidence is not so clear as in Kinta. However, these two localities are the only places known to me where overfolding is evident or suspected. The balance of evidence is of compressed, plicated, and faulted anticlines and synclines.

Faulting of the strata I believe to have taken place on a large scale, accompanied by "magmatic stoping." The evidence for the latter will be mentioned in the more detailed description of the coulisses.

Denudation in Tertiary and recent times has laid bare the skeleton of the Peninsula, but it has not reached the granite or associated plutonic rocks everywhere, therefore the Peninsula, apart from the difficulties created by the vegetation, forms an admirable field for observing the form of the upper limits of the granite ribs, and the way in which the granite surface plunges along its strikes under stratified rocks, is capped by them, emerges as small outcrops, or sends out veins into the stratified rocks.

In the northern portion of the map (Fig. 2), is seen the southern end of the Nakawn coulisse. I have examined this only on the Perlis border, and in what may be its prolongation in the Langkawi

[1] Ipoh, marked on the map, Fig. 2, is in the Kinta District.

Islands. A view of the Nakawn hills, however, from the railway in Siamese territory, suggests that they are granite. On the Perlis border granite is found in the north (Gunong China, 2,370 ft.), but it plunges under a thick cover of limestone, which forms rugged hills along the border to the sea. This range of limestone hills contains, near the granite, deposits of tin-ore that are worked in caves. It curves slightly toward the west before it reaches the sea, which suggests that the similar rugged limestone hills of the Langkawi Islands are part of the same coulisse. In these islands, however, granite reappears in Gunong Raya (2,888 ft.) and other outcrops.

The Kedah-Singgora Coulisse (No. 2) is a broader range of shale and quartzite hills of no great altitude, in which a few outcrops of granite have been found, but Bukit Tinggi, the principal peak (2,525 ft.), is formed of the sedimentary rocks. Tin and wolfram deposits in its neighborhood prove, however, that granite cannot be far below the surface. These hills extend northward to the China Sea, and are crossed in Siamese territory by the railway to Kelantan. Cuttings on this railway show a large granite outcrop between outcrops of quartzite.

South of the range are isolated outcrops which may have once been continuous with it, but have been separated by marine denudation, converting them into islands in a sea covering the plain of Kedah and Province Wellesley. The first of these (No. 3) is Gunong Perak (2,823 ft.), an isolated granite mass. Number 4 is a more imposing mountain, Kedah Peak or Gunong Jerai (3,978 ft.), formed of quartzite with granitic intrusions. Penang (No. 5) is still an island. The only rock other than granite that I have seen there is dolerite, and I have not seen that in situ. The main mass of the island is certainly granite, rising to 2,722 ft.; but to the southeast are two small islands of sedimentary rocks. In Province Wellesley are granite hills with a few of sedimentary rocks also.

The Bintang Coulisse (No. 7) is the first large granite range in this part of the Peninsula. It has been broken by marine denudation between Taiping and the Dindings, and farther north, between Gunong Bintang (6,103 ft.) and Gunong Lang (3,750 ft.) is a comparatively low tract of stratified rocks, the granite being seen only

in low country to the west of it. In the headwaters of the Patani River the granite hills continue and end west of the Patani River near the sea.

Near Taiping are two interesting outcrops of limestone. On the west of the Bintang Coulisse is a limestone hill, Batu Kurau, nearly surrounded by granite. On the east of the coulisse is a better-known limestone hill, Gunong Pondok, visible from the railway, which may be entirely surrounded by granite: a covering of alluvium on one side makes this doubtful.

The largest granite range of the Peninsula is that generally known as the Main range (No. 9, the Kerbau Coulisse; Gunong Kerbau 7,160 ft.), and between it and the Bintang Coulisse is a small granite range (No. 8, the Kledang Coulisse) which dips under altered sedimentary rocks at either end. At the northern end of this range are two peaks, Gunong Soh (4,336 ft.) and Gunong Besar (5,725 ft.), but this granite dips under schists and sheared quartz-porphyry of the Pahang Volcanic Series immediately north of the east-and-west reach of the Perak River (see map). Gunong Soh and Gunong Besar are the highest peaks in this granite mass and are connected by low-lying granite areas with the Bintang Coulisse on one side, and the Kerbau Coulisse on the other. Farther south there is a break in the granite hills where a tributary of the Perak River cuts through the range north of Kuala Kangsar. Here the granite almost entirely vanishes below the surface: a strip of older sedimentary rocks and one of the small patches of Tertiary rocks (containing limestone) break the continuity of the granite except for a small exposure in the Perak River. Both in this range and in the Bintang Coulisse there is evidently a dip in the profile of the granite ridge. In the Bintang Coulisse it involves a drop on the steeper side of about 5,000 feet in 8 miles, an incline of roughly 1 in 8; in the Kledang Coulisse there is a drop on the steeper side of about 2,000 feet in 2 miles, an incline of roughly 1 in 5.

Farther to the south the granite of the Kledang Range, forming peaks of between 2,000 and 3,000 feet, dips under quartzite, which forms a lower continuation of the range until it dies away in the alluvium of the Perak River.

In the country between the north part of this Kledang Coulisse and the Bintang Coulisse, an area that is low-lying, there is, as

already stated, granite connecting the two. In this granite there are, in the neighborhood of Lenggong, about 30 miles north of Kuala Kangsar, small hills of crystalline limestone surrounded by the granite, which appear to be portions of the Carboniferous limestone stoped away from the cover and prevented from sinking farther by the viscosity of the magma. They contain secondary minerals commonly found at such contacts.

Farther to the south, in the Kinta District, mining operations in the valley of a stream, the Johan, that rises in the Kledang range, have revealed another island of limestone in the granite.

The Kerbau Coulisse (No. 9) is the most arcuate of all those in the Peninsula, a pronounced bend existing about half-way along its course. The northern half is the higher, with several peaks above 7,000 feet and along part of the northern half the descent is steeper into Kelantan than into Perak.

In the extreme north, in the neighborhood of Tomo, the details of the coulisse are not yet accurately known, but south of Tomo recent journeys have brought to light an interesting structural point. On the map a sharp curve can be seen in the boundary between Perak and Kelantan, about twenty miles south of Tomo. Here a granite mountain, Gunong Noring (6,194 ft.) visited in 1922 by Mr. H. E. Savage, is, approximately, the end of the granite outcrop along the watershed. A little north of Gunong Noring the granite outcrop bifurcates, one fork passing through the headwaters of the Perak River into Siamese territory between the Patani and Telubin rivers, the other trending northeast. Part of the intervening country is still unsurveyed, but it is believed that the northeast branch ends in hilly country east of Tomo. In between these two forks of the granite ridge are altered sediments with small outcrops of granite-aplite, hornblende-granite, and diorite, evidently apophyses from the main mass below the sediments.

In both forks the granite is often gneissose owing to flow in the magma. It is rich in biotite; and in the western fork I have found a large outcrop crowded with xenoliths of mica-schists, showing that denudation has not removed much granite.

The highest portion of the granite ridge in the Kerbau Coulisse is in the neighborhood of the junction of the boundaries of Perak, Kelantan, and Pahang. Here are three peaks of over seven

thousand feet, and a little farther north are two more. Of the three near the junction of the state boundaries, one, Kerbau (7,160 ft.) is known to be capped by altered sediments, so that on this mountain we have the original limit of the granite ridge.

Farther south than Kerbau, just on the bend of the coulisse, a large outcrop of schists and quartzite is known on the Pahang side at an altitude of three to four thousand feet, surrounded by granite; and on the opposite side of the range, at Chanderiang, a long tongue of limestone, under alluvium worked for tin-ore, is almost surrounded by granite. Farther south still, in Selangor, there is another outcrop of calcareous rocks in the granite at Kanching, part being a prominent limestone hill, and also an outcrop of altered sedimentary rocks in the granite near Kuala Kubu.

In the southern half of the Kerbau Coulisse the granite hills fall away gradually. Near the bend Batu Puteh is 6,987 feet. Near the Selangor border Gunong Liang is 6,431 feet; in Selangor Ulu Kali is 5,820 feet. In Negri Sembilan the mountains are under 4,000 feet, and in Malacca they die away altogether; but the coulisse is continued to Banka, the intervening gaps being caused by marine denudation.

In Selangor and Pahang tin-deposits are found high up in the mountains of this coulisse, in some cases on the watershed. As tin-deposits in a granite mass are generally peripheral, this suggests that little granite has been removed from the top of the ridge by denudation.

On the east side the Kerbau Coulisse is flanked in Pahang by a well-defined range of quartzite foothills. Beyond this, at Raub and to the north and south of Raub, the calcareous series is exposed over a wide area until the Benom Coulisse is encountered. The calcareous rocks are found to the east of this coulisse also, in the wide valley of the Pahang River, and are there covered in places by sandstone and shale in which there is a Rhaetic horizon, the Myophoria Sandstone described by Mr. R. B. Newton.[1] In the Benom Coulisse the only high peak is Gunong Benom, 6,916 ft. The rock is mostly hornblende-granite; there is some syenite. To the north the plutonic mass disappears under the sedimentary and calcareous

[1] *Proc. Malacological Society*, Vol. IV, Part 3 (October 1900), pp. 130–35.

rocks before reaching the Kelantan border, a few small outcrops of granite and granite-porphyry only being found. To the south it continues into Negri Sembilan, where it disappears under the calcareous series close to the granite of the Kerbau Coulisse. Hornblende-granite has not been found at this end, but Mr. E. S. Willbourn mentions boulders of quartz-diorite.[1]

Beyond the Kerbau and Benom Coulisses is Mount Ophir (No. 11), 4,187 feet. This is an isolated mountain of granite, but, it may be assumed, connected at no great depth with the granite of the Kerbau Coulisse, which, in turn, must be connected at no great depth with the granite of the Benom Coulisse, the last-named being best regarded as a large spur given off by the Kerbau Coulisse.

To the north of the Benom Coulisse there is a large tract of country in Kelantan that has been only partially explored. In the vicinity of Pulai muscovite-aplite intrusive in limestone may be connected with the Benom granite. Farther north, in the branch of the Kelantan River rising in the Kerbau Coulisse, and on the line of strike of the Benom granite, pyroxene-granite-porphyry, biotite-granite, and pebbles of a hornblendic rock, probably diorite, have been found in country largely consisting of limestone. If the line of strike is continued farther still, it joins the Kerbau Coulisse south of Tomo, and in the neighborhood of Tomo are the small intrusions of diorite and hornblende-granite mentioned above. This line of strike of the Benom granite, from Negri Sembilan in the south, through Pulai, to Tomo in the north, passes through the gold-bearing belt of the Peninsula, which is sharply differentiated from the chief tin-bearing belt to the west. Much of the gold has been derived from rocks of the Pahang Volcanic Series, but some is found in country where the hornblende-granite and diorite occur, these appearing to be the source in certain areas. Continued work may reveal something more definite about the relation of these hornblendic rocks in Kelantan to the granite of the Kerbau Coulisse and the rocks of the Benom Coulisse.

East of the Benom granite in Pahang and in the country about Pulai in Kelantan, limestone is abundant, but it ends abruptly

[1] "An Account of the Geology and Mining Industries of South Selangor and Negri Sembilan," *Geol. Dept. F.N.S.*, 1922, p. 35.

against a broad outcrop of quartzite forming rugged hills and rising, on the Pahang-Kelantan border, to a height of 7,188 feet (Gunong Tahan, the highest mountain in the Peninsula). This mass of quartzite (No. 12) falls away to the north of the Pahang-Kelantan border, but southward it extends beyond the Pahang River. In the extreme south of Pahang and in Johore granite hills occur, and outcrops of quartzite also, which are assumed to form a continuation of this "Tahan Coulisse"; and in Singapore Island the granite and quartzite appear again, the latter weathered to sandstone with Myophoria and other fossils.

In the south this band of quartzite and granite is broken by marine denudation. There are certainly intrusions of granite. In the north the outcrop of quartzite is rugged, continuous, and on the Pahang-Kelantan border, very high, but I have not seen any granite outcrops in it, or any veins of aplite, or evidence of the proximity of granite, such as tourmalinization. The nearest granite known to me is a small outcrop close to the western edge of the quartzite east of Pulai, but it is intrusive into limestone country. It may be that, in the northern part, this mass of quartzite owes its prominence simply to its power of resisting denudation, but there is, as already mentioned, some evidence of folding, and in view of the fact that the prolongation of the Peninsula to Singapore is due to its existence and that of the hills marked 14, 15, 16 in Figure 2, I think it is justifiable to name it the Tahan "Coulisse."

The last of the ribs of the Peninsula is that marked 14, 15, 16 on the map. This may conveniently be referred to as the East Coast Coulisse. Recent work shows that in the north it is a definite granite range rising in Kelantan close to the sea. The granite certainly extends a long way down the Trengganu border, and it is believed that it reaches the Pahang border, where the coulisse is continued in hilly country of granite and altered sedimentary rocks. These are broken by the alluvial plain of the Pahang River, but continue to the south as hills of sedimentary rocks with at least one granite outcrop. On the Johore border large outcrops of granite are known, and in Johore the coulisse is continued as more outcrops of granite and sedimentary rocks, with volcanic rocks of undetermined age, until it ends in the point east of Singapore. The

granite of this coulisse is tin-bearing in the north of Pahang, the South of Pahang, and in some localities in Johore. Tin and wolfram deposits in Trengganu are probably connected with it, and in Kelantan a little tin-ore is reported in it. It forms another tin-bearing belt, not so well-defined as that formed by the Kerbau Coulisse and other coulisses to the west of it. The gold-bearing belt lies between the two.

The island of Tiuman consists mostly of granite. The numerous small islands nearer the coast are of rhyolite and granite.

The Peninsula then has a skeleton of granite ribs from which denudation has not yet removed the whole covering of bedded rocks. In some cases, such as those marked on the map as Nos. 1 and 2, the thickness of the cover remaining is considerable. In No. 9, the Kerbau Coulisse, a small portion of the cover remains perched at an altitude of 7,000 feet. Islands of schists and quartzite are known at lesser elevations in No. 9, and masses of limestone are found totally surrounded by granite on the surface in Nos. 9 and 8, all parts of the cover.

These granite ribs are arranged *en échelon:* no one range can be said truly to be the backbone of the Peninsula; but if we refer to Figure 1, or Figure 72 on page 147 of Professor Hobbs' book, we see that they are but the detailed wrinkles of one great band of folding that sweeps through the Peninsula and then, turning NE, through the northern part of Borneo to the Philippines.

Owing to the amount of the cover remaining, one can obtain a fairly good idea of the profiles of the granite ribs when they first consolidated. In Figure 2 I have drawn a line through some of the coulisses, connecting the highest outcrops of granite. This line, starting at No. 3 (Gunong Perak, 2,823 ft.), and extending as far as Benom, will be seen to have the same general direction as that of the curve of the arc through the Peninsula and Borneo just referred to. The line might be produced in the same direction to No. 13 (Gunong Besar, 3,403 ft.) but there is some doubt about its being all granite. In the East Coast Coulisse the highest granite is far to the north of Gunong Besar. This line, however, joining the highest parts of the granite profiles of 3, 7, 8, 9, and 10, is interesting as showing the probable trend of the first emergent

land when the denudation of the cover began, which was, as far as we can tell, in late Mesozoic times (in the Archipelago Eocene beds contain granite pebbles). To the east, the quartzite of the Tahan massif and the granite of the East Coast Coulisse formed another mass of superior resistance determining the extension of the land in that direction.

In my paper in the *Geographical Review* I sketched the history of the Peninsula and Archipelago in Tertiary and recent times (pp. 353, 354). In Miocene times there is reason to believe that depression converted the Archipelago into a few small islands and that later "a gradual elevation occurred which ultimately united the whole of the islands with the continent."[1] This depression must have affected the area that is now British Malaya, and it was marine denudation connected with this depression, then subaerial denudation when the uplift occurred, and marine denudation connected with another depression in recent times, that revealed the true course of the granite intrusions, and made the breaches in the Bintang and Kledang Coulisses where the granite dips under the older stratified rocks. In the case of the Kledang Coulisse, if the patch of Tertiary rocks occurring in the gap is Miocene, the breach was effected in Miocene times.

The effect of marine denudation has been great. It is particularly noticeable in Johore, where the granite and other hills rise like islands from a gently undulating plain, and in Perlis and Kedah, where some of the hills are even more striking in their resemblance to islands.

In the basin of the Perak River there is, above Kuala Kangsar, evidence of the continuity of the granite between the coulisses. The granite of the northern end of the Kledang Coulisse (No. 8) is connected on the surface with that of No. 9 on the one hand and that of No. 7 on the other. The granite of Gunong Perak also (No. 3) is connected by comparatively low-lying outcrops with that of the Bintang Coulisse, but elsewhere the granite outcrops of one coulisse are separated from those on either side by stratified rocks.

The granite outcrop connecting Gunong Perak with the Bintang Coulisse strikes only a little to the north of Gunong Bintang, the

[1] Dr. A. R. Wallace, *Island Life*, pp. 385, 386, 390.

highest point; so here we have a continuous granite outcrop from Gunong Perak to a part of the Kerbau Coulisse where there are two peaks of over 7,000 ft. Between Nos. 9 and 8 the country is fairly high on the granite outcrop, but between 8 and 7, and 7 and 3, it is only about 300 feet above sea-level.

The strike of this continuous granite outcrop, across the coulisses, is, as can be seen from Figure 2, on which I have shown the granite by a conventional sign, roughly parallel to the axis of the Peninsula, and to the curve of the Peninsular-Bornean arc, and shows the roof of the bathylith (containing near Lenggong, as already noted, isolated blocks of limestone from the cover). Between 9 and 10, however, the granite dips steeply under the older bedded rocks near the line of highest granite points. The land is not high: Raub is only 462 feet above sea-level, Bentong only 321, but at Raub a shaft 900 feet deep shows no granite, or signs of its proximity, other than the occasional occurrence of scheelite in the gold-bearing veins. In the Benom Coulisse it rises again sharply and falls away sharply on the other side under the Pahang Valley.

Granite is not entirely confined to the coulisses on the surface. In the low country between them small outcrops are found. Some form distinct landmarks, for instance a hill at the mouth of the Selangor River, and another on the coast near Kuala Lumpur.

The composition of the granite and other igneous rocks in the coulisses raises interesting problems that would be out of place to discuss here. I will mention one point in this connection only, that the summit of Kinabalu (13,698 ft.) at the far end of the Peninsular and Bornean arc, is formed of hornblende granite.

There remains one point in the structure of the Peninsula to be mentioned, the influence of faulting in the cover of stratified rocks on the formation of limestone hills, which sometimes exceed 2,000 feet in height. The limestone hills I have mentioned in a granite-area near Lenggong, and again at Kanching, and those almost surrounded by granite, Batu Kurau and Gunong Pondok, suggest block faulting; but the majority of the limestone hills are not in the granite-areas. The greatest development of them is found in the Kinta District, where their distribution and height above the limestone floor of this tin-field suggest block-faulting on a large

scale, and the suggestion is strengthened by vertical limestone cliffs overlooking the granite of the Kerbau Coulisse, by small patches of phyllites lying between the base of these cliffs and the granite, and by a brecciated iron-ore deposit at the base of one of the hills. In Perlis again a double line of limestone hills runs north and south through the center of the state, rising from shale and quartzite country, but here there is a possibility of the latter being older than the limestone. In other states I have not seen any evidence of faulting having formed blocks which denudation has converted into limestone hills. I may mention in this connection that Dr. W. C. Klein, who has studied the geology of northern Sumatra, where limestone hills also occur, tells me he considers that faults are of structural importance and affect the limestone. In Borneo also, the late Mr. J. S. Geikie attributed the formation of the limestone hills of the gold-bearing area of Bau and Bidi in Sarawak to faulting.[1] I have seen the limestone hills at Bau and Bidi and found the evidence of faulting determining their formation very strong, and clearer than in the Kinta District, where the earth-movements have been more intense.

In Sumatra Dutch geologists recognize earth-movements later than the Mesozoic folds. In the Peninsula these are marked by faults in the granite, and in some places, as in Negri Sembilan, by shearing of the same rock, but they are not known to be of any structural importance.

[1] J. S. Geikie, "The Occurrence of Gold in Upper Sarawak," *Trans. of the Inst. of Mining and Metallurgy,* Vol. XV (1905–6), pp. 65, 66 and Fig. 1 on p. 65.

THE FERRUGINOUS CHERT FORMATIONS OF NOTRE DAME BAY, NEWFOUNDLAND[1]

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OUTLINE

SUMMARY

This paper describes ferruginous cherts which for the most part are found as beds of very uniform thickness in sections composed largely of volcanic rocks. The author considers the cherts to be chemically precipitated sediments.

[1] Part of a thesis submitted to the faculty of Princeton University in candidacy for the degree of Doctor of Science, 1920.

The rocks of the region vary from Cambrian to Silurian age and are, for the most part, of volcanic origin, pillow lavas being abundant and developed to great perfection. The author believes that widespread pillow lavas, such as are found in Notre Dame Bay, are formed by subaqueous extrusion.

There are three types of chert. The first is found in the interstices of pillow lavas, the second as heavy beds of jasper found with acid tuffs, and the third as thin beds interbedded with acid tuffs. The bedded chert contains radiolaria but only as incidental fossils. Cherts of these varieties have been described from many parts of the world and some of the more important occurrences are cited. The geologic occurrence in every instance presents features in common with those of Notre Dame Bay. Particularly is this so of the radiolarian cherts of Scotland.

The silica of the cherts is thought to have been contributed to a marine basin principally by magmatic emanations from submarine vents or fissures. Processes are suggested by which precipitation might have been brought about, the most important being the precipitation of colloidal silica by the ions of sea water having an opposite charge and, to a less degree, by oppositely charged colloids formed by the interaction of magmatic and sea water.

FIELD WORK

This paper is a report on a portion of the field work carried out by the Princeton University Geological Expeditions to Newfoundland of the years 1915, 1916 and 1919. Most of the work was of a reconnaissance nature covering Notre Dame and White Bays. In 1919 Notre Dame Bay was revisited and detailed work was done. Though most of the work was on the copper mines, special attention was given to the chert localities.

ACKNOWLEDGMENTS

It is a pleasure to make the following acknowledgments. Dr. Arthur F. Buddington and Dr. William M. Agar were both associated in part of the field work. They made the work possible and have contributed much in discussion of the geology of the region. Mr. Allan C. Brown and Mr. Hiram Blauvelt were each in the field

one season and cheerfully and efficiently assisted in the work. Professor Gilbert van Ingen, who organized the Princeton University Expeditions to Newfoundland, has by the stimulus of his interest aided the work of which this report represents a phase. Dr. Rudolph Ruedemann has identified and correlated the grapolites. This report was written under the direction of Professor C. H. Smyth, Jr., and it is a pleasure for one of his former students to acknowledge the inspiration of his teaching and influence, even though this paper so little reflects it.

GENERAL GEOLOGY

A map showing the general location and some details of the geography as copied from British Admiralty charts is given in Figure 1.

The general distribution of the rocks in Notre Dame Bay is such that the oldest formations are found on the north side of the bay and on the outer headlands of the west and south sides. Going inland, south and west, up the fiord bays younger formations are encountered of Ordovician and Silurian age. At a few places in these younger formations highly fossiliferous rocks are found. Professor van Ingen reports that all faunas show a marked affinity to those of Great Britain, and range in age from Llandeilo of the Ordovician, to Llandovery, or perhaps Wenlock, of the Silurian. The similarity of the geologic history of these two regions in Ordovician and Silurian time is remarkable.

Throughout the whole district the structure is exceedingly complex. Faulting is highly developed, but folding is not conspicuous and is seldom observed although dips are high, often vertical.

Several series of rocks can be recognized, the oldest being volcanic.

CAMBRIAN (?)

One great series is composed very largely of andesitic pillow lava with minor amounts of basic breccia and tuffs of variable composition. Ordinary sediments appear to be lacking. Chert is often found on the spaces between the pillows, and also with heavy beds associated with tuffs. In places there are exposed great sections of tuffs, breccias, and flows which show no pillow

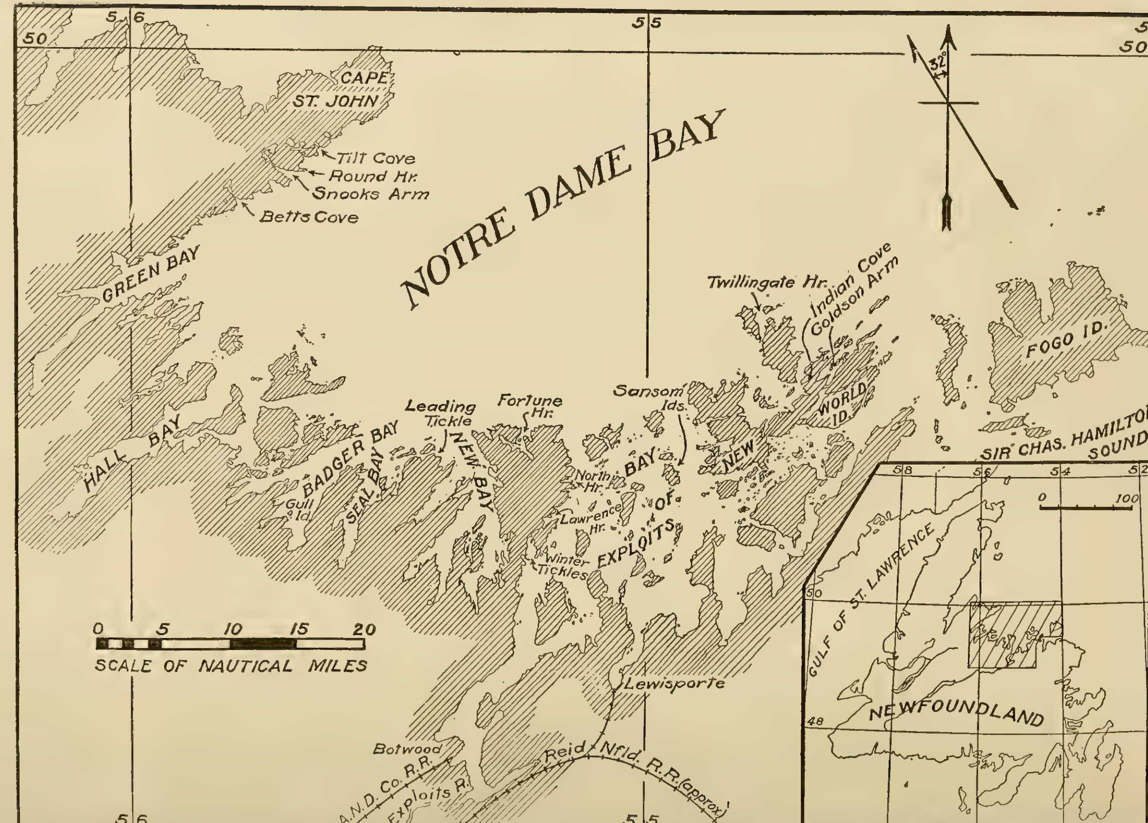

FIG. 1.—Map of Notre Dame Bay, Newfoundland, showing localities mentioned in text. Based on British Admiralty charts.

structure. Such sections do not contain chert. These sections are not simply different facies of the pillow lava series, but are thought to represent a distinct series. As to the age of these two series, evidence is scanty. That the first mentioned series containing chert is considerably older than the Upper Ordovician is indicated by the relative degree of metamorphism, and particularly by the finding of its characteristic green chert in conglomerates of Upper Ordovician age. This series is probably of Cambrian age. As to the other series which does not contain pillow lavas or chert, we can only say that it is intermediate in age between that of the old pillow lavas and the Middle Ordovician.

ORDOVICIAN

The known Ordovician rocks are represented in the lower sections by volcanics and shales. The volcanics are principally pillow lavas of andesitic composition and tuffs which are mostly acid. Throughout Notre Dame Bay rhyolite flows are practically absent, the rhyolitic eruptives being clastic and represented principally by tuffs which show somewhat waterworn fragments. Thin beds of chert are often found associated with these tuffs. In some places, the volcanics are wanting, and shales containing beds of chert take their place, though a persistent black graptolitic shale fixes the age of these rocks as contemporaneous with sections showing volcanic products. The graptolites are of Llandeilo age. In the higher sections, there are sandstones and some conglomerates, both of which are commonly red. In places on the east side of New World Island, limestones of Caradoc age are associated with pillow lavas and volcanic breccias, some of which breccias have a lime cement. At Burnt Arm, branching from Goldson Arm, a pillow lava was seen with fossiliferous limestone in the spaces between the pillows. The lime mud must have been caught up when the lava was extruded. Here, at least, the evidence for the subaqueous nature of the pillow flows is clear.

SILURIAN

The Silurian rocks are principally sandstones and conglomerates, usually red. Very thick sections are exposed, those studied being in the extreme south of the bay and on the Exploits River. They are

in places highly fossiliferous. Volcanic rocks are almost entirely absent in the known Silurian. No chert has been found in the Silurian or in the upper part of the Ordovician.

Intrusive igneous rocks are abundant and varied and greatly complicate the structure of the region, but as they have no bearing on the present problem they need not be discussed.

DISTRIBUTION OF CHERTS

The area in which the cherts occur on the coast is clearly limited, as they are confined to that portion within which the pillow lavas are found. The pillow lavas are thick conspicuous formations which in this part of the Newfoundland coast do not occur north of Cape St. John nor east of New World Island. Within Notre Dame Bay they are exposed at many places.

VARIETIES OF CHERT AND ASSOCIATED ROCKS

GENERAL STATEMENT

Wherever the cherts have been observed, with the exception of only one occurrence, to be considered later, they are intimately associated with volcanic rocks. Three general modes of occurrence are recognized: first, in the spaces between pillows; second, as heavy beds of jasper associated with acid tuffs; and third, as thin beds of green chert, associated with tuffs, in sections which are made up principally of fragmental material and shale. The first type, interstitial, occurs in the oldest pillow lava series of probable Cambrian age; the second type, heavy beds with tuff, is probably also of the same age; and the third type, which consists of thin beds, is in several widely separated localities in close proximity to the black graptolitic shale above referred to and is probably of the same age, Llandeilo. Pillow lavas are found in some of these sections though not in immediate association with the chert beds.

The flows of pillow lava, throughout the region, are commonly from 50 to several hundred feet thick. Individual pillows vary greatly in size, being sometimes as much as 10 feet in diameter, but the average greatest cross-section is about three or four feet. They usually approach spherical form, but quite commonly bolster-like masses are found. They are exceedingly massive and very

rarely show hollow centers. Concentric rings of amygdules are frequently seen and variolitic structure is common, the variolites increasing in size and number toward the center where they coalesce to form a dense crystalline rock. Variolites are seldom over a centimeter in diameter, and in most cases but a few millimeters. The variolitic shell ranges in thickness from a few millimeters to 10 or 15 centimeters or even more. Pahoehoe lava and the various ropy forms so characteristic of subaerial flows are absent. In Notre Dame Bay pillow lavas are probably shown in as great perfection and profusion as in any other region yet described.

Although recognizing that pillow lavas may form on a small scale on land, the author believes that a review of the literature justifies the conclusion that a thick series of pillow lavas, covering a wide area and free from pahoehoe and massive flows, is in all probability a subaqueous flow, and such an origin is accepted for the pillow lavas with which the cherts in question are associated.

FIRST TYPE—INTERSTITIAL

The first type of chert to be considered in detail is that which occurs in the spaces between the pillows. The chert is found in irregular masses conforming to the pillow surfaces and seldom over eight inches in greatest dimension. The chert does not replace the surrounding rock which shows the usual gradational changes through variolitic or amygdaloidal structure to the tachylitic crust next to the chert. Good exposures of chert in pillow lava may be seen at Round Harbor, the bottom of Snooks Arm, the Betts Cove copper mine and on the southwest shore of the Northwest Arm of Fortune Harbor.

SECOND TYPE—HEAVY BEDS OF JASPER

The second manner of occurrence of the chert is in heavy beds associated with rhyolitic tuffs and forming part of the old (Cambrian?) pillow lava series. The chert in this association is usually a bright red jasper and in places it is very dark red, due to a considerable manganese content. As the associations are so much the same in widely separated localities, these rocks may form a distinct member of the series.

The jasper of this formation forms beds as much as 25 or 30 feet in thickness, though the zone through which these heavy beds occur is probably not greater than 100 feet. However, at the Southeast Arm of Fortune Harbor, where the Jasper is apparently overlaid by several hundred feet of tuff, these tuffs contain many thin beds of red and green chert a few inches in thickness.

Good exposures are to be seen at the following places: the north shore of Goldson Arm and the north shore of Indian Cove, both on New World Island, and in several places in Fortune Harbor, particularly at the two places where prospecting has been done on the beds for their iron or manganese content. There is also exposed on the trail from Round Harbor to Tilt Cove a very heavy bed of jasper apparently in the same association as the others, but at this place the very dense underbrush obscures the relations.

Some of the occurrences of this type of chert contain radiolaria. These will be described under the microscopic features.

THIRD TYPE—THIN BEDS

There remains one type to be described, the third type, which occurs interbedded with a peculiar siliceous shale and often with rhyolitic tuffs. This type of chert is exposed at the following places: the northern part of the western shore of Sansom Island; between North Harbor Head and North Harbor on the Ship Run of the Bay of Exploits; at Lawrence Harbor and also on the east side of Winter Tickle, both on Ship Run; on the south side of Leading Tickle, at and near the Ladle; and on the small islands south of Gull Island in Badger Bay.

These exposures have many features in common. The prevailing type of chert is a green variety, having a porcelain-like texture and a very perfect conchoidal fracture. In places thin beds of jasper are of minor importance. The chert is usually interbedded with tuffs.

The individual beds of chert are thin, being rarely over a foot thick, often from three to six inches thick, and in places less than one inch thick. The thickness of individual beds is of great uniformity and the beds are persistent. In this respect, as in many others, they resemble some of British radiolarian cherts of the same

age, but they are in marked contrast with those of the Franciscan Series of California. This type of chert in Notre Dame Bay commonly contains radiolaria.

The tuffs associated with the chert are composed largely of crystal fragments among which quartz usually predominates. Both potash feldspar and soda-rich plagioclase are present together with a considerable amount of fine-grained devitrified glass. All the fragments are angular and are contained in a very fine-grained ground-mass. Delicate structures such as shards of glass seem to be entirely lacking, the material probably having been sufficiently waterworn to have destroyed them. Beds of shale are common, but many of them are of a peculiar nature, perhaps originally containing some gelatinous silica. The whole chert, shale, and tuff series is frequently associated with pillow lavas.

In one place chert of the thin-bedded type is found where there are no volcanic rocks in the section, but there is reason to believe that these chert beds were formed contemporaneously with volcanism elsewhere in the district. In Badger Bay, on the small islands south of Gull Island, a section is found which resembles those of Leading Tickle and Lawrence Harbor and like them is in close proximity to beds of black graptolitic shale. On these islands thin beds of chert are well exposed, but the tuffs which form parts of the other sections are absent. However, the black graptolitic shale fixes the age as contemporaneous with the volcanic rocks of the other sections.

This section, which probably represents about 2,000 feet of sediments, is composed largely of varieties of a peculiar shale. In the hand specimen it is a hard dense rock, where cleavage is not highly developed. The commonest colors are green and gray. It is rather thin-bedded and free from carbonate. In parts of the section, portions from 50 to 100 feet thick are predominantly red and in or near these red portions thin-bedded chert is found. There is probably a considerable admixture of cherty silica in these shales.

The most interesting feature of these red shales is the great profusion of radiolaria at some horizons. The shale rich in radiolaria usually shows them in the hand specimen as light specks. These can readily be seen if the rock be smoothed off with a whet-

stone and then moistened. This test was found useful in the field. In one bed near the westernmost point of Gull Island, the radiolaria appear like abundant white sand grains in the red matrix of the rock.

The cherts of this locality show almost no radiolaria. It is believed that these chert beds were formed much more rapidly than the enclosing shales, and that they are free from radiolaria and impurities because of this rapidity of deposition.

COMPOSITION AND STRUCTURE

To avoid repetition, the green varieties of chert will be described together followed by a description of the red varieties. There is a fundamental relation between the present color of the chert and the manner in which it has been formed.

Green Chert

Green chert is found in the first and third types—interstitial and thin-bedded. In both types it appears to be of much the same nature. Most thin sections show an extremely fine aggregate of interlocking grains of quartz, the largest grains in different thin

Analysis of 2-inch Bed of Green Chert (260 Y 16 *a*) from West Side of Lawrence Harbor, Ship Run, Bay of Exploits, Notre Dame Bay, Newfoundland

SiO_2	85.78
Al_2O_3	5.68
Fe_2O_3	2.92
FeO	2.09
MgO	.25
CaO	.48
Na_2O	.68
K_2O	.36
$H_2O\pm$	1.88
	100 13

sections varying from about 0.05 mm. to as little as 0.02 mm. In every case most grains are considerably smaller than the largest, generally about 0.005 mm. Some sections contain isotropic silica and in these there is a gradation from the isotropic area into the crystalline area, crystallization starting at scattered nuclei.

All sections show more or less cloudiness at low magnification. At very high magnification the impurities can be distinguished as specks. They are in the form of plates and appear to have a faint green color. The index is well above quartz. Under crossed nicols most grains cannot be distinguished. One specimen of this variety of chert was analyzed. It contains more than the usual amount of impurities and was selected in the hope of shedding light on their nature. The analysis is shown on page 580.

Some of the larger grains of the green mineral in this specimen show, in addition to the above-mentioned properties, a distinct pleochroism and when seen on edge a moderate birefrigence and an extinction nearly or quite parallel. This analysis throws some light on the mineralogic composition of the chert. Most important is the amount of ferric iron. If this were not combined the rock would surely have a red color. The presence of a ferrous-ferric silicate seems clear. It may be noted that with the union of similar bases the ratio $Al_2O_3:FeO:Na_2O$ is almost precisely 5:3:1. However, as the amount of all the minor constituents is so small no great weight is to be attached to this. It is possible that the alkalies may be adsorbed by the silica. Their quantity is much less than the amount required by glauconite and the amount of alumina also points away from that mineral. There seems to be, however, little doubt that there is present an alumina-ferric-ferrous-silicate with probable alkalies. Assuming 5 molecules of silica and 6 of water, there would be present about 19 per cent by weight or 16 per cent by volume of a mineral having a density about equal to thuringite. This quantity, which is of course only a rough approximation, seems consistent with observation, though the grains are too small and their boundaries too ill-defined for exact measurement.

Red Chert

Thin sections of red chert are for the most part opaque. Some sections are entirely so, but others are not uniformly opaque. In these last the opacity is seen to be caused by extremely minute red specks of iron oxide. The distribution of these is not uniform but is without system. Most of the area is opaque, the more translucent portions being in the form of clouds within the opaque

areas. The silica in many sections is amorphous, as in the case of the green cherts. In many thin sections of the second type of chert and of the red beds of the third type radiolarian tests can be clearly seen. The tests are of clear quartz. The radiolaria are of extremely simple structure; none of them show spines, and it seems improbable that they ever possessed any. The commonest forms are spherical. Many have a clear center and consequently show no shell. They range from 0.20–0.30 mm. in diameter. Others are annular in section and about the same size. The central part of these forms is filled with opaque jasper. In the shales associated with the thin beds of chert at islands off Gull Island in Badger Bay, there is a profusion of forms having an elliptical annular section varying from 0.15×0.20 mm. to 0.30×0.50 mm. besides very abundant smaller circular forms. In these shales the radiolaria are preserved in great perfection, the boundaries being exceedingly sharp. Only one individual was observed having a slight protuberance and none were observed with any spines.

One occurrence each of the interstitial and of the heavy bedded jasper give evidence of diffusion phenomena having taken place while the silica was in a gelatinous condition. This is best illustrated by the jasper of the Sweeny manganese prospect at Fortune Harbor. Here 30 feet of jasper is to be seen, which lies between 70 feet of pillow lava and a tuffaceous sandstone probably at least 50 feet thick. About 15 feet of this jasper is manganiferous; an aggregate sample of pure unweathered jasper yielded 5.16 per cent Mn. This manganese has been further concentrated on joints.

The manganiferous and nonmanganiferous jasper of this locality show features which are interpreted as having been formed in gel. The most striking features are found in the nonmanganiferous portion illustrated in Figures 2, 3, and 4. In Figure 2 the dark areas represent opaque jasper, and the clear areas silica with cloud-like specks of iron oxide. These are shown in Figure 3 which is a portion of the same field as Figure 2. It is to be noted that all areas, regardless of size or shape, are surrounded by a clear band about 0.004 mm. thick and outside that a dark band somewhat thin-

ner. This structure is most readily explained as caused by precipitation by diffusion. The whole sectem is now composed of crystalline quartz, the boundaries of the grains showing no relation to the structure described. Another part of the same section is illustrated by Figure 4. The clear central areas contain minute cherry red plates presumably of hematite. The boundaries of these crystals

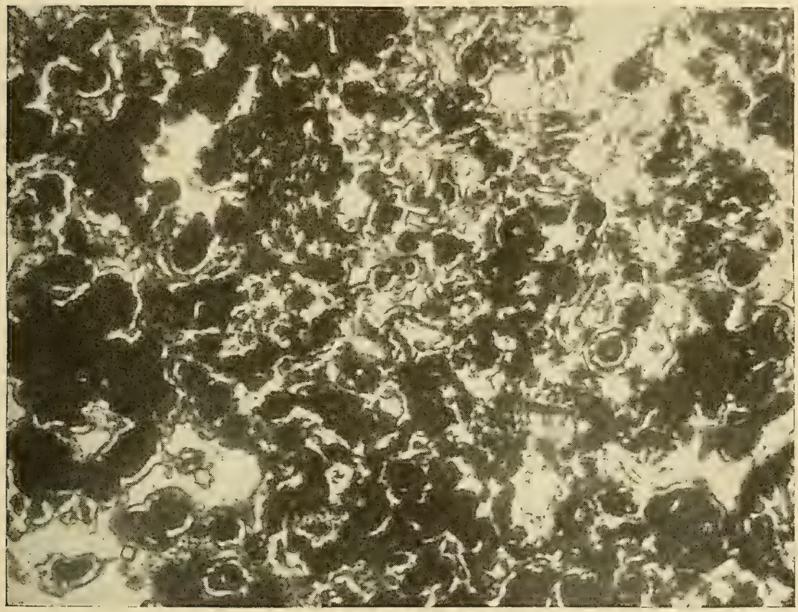

FIG. 2.—Thin section (No. 211) of jasper from Sweeny manganese prospect, Fortune Harbor. Shows banding in what is thought to have been colloidal silica. Section now composed of quartz whose crystalline structure is entirely independent of the original structure of the rock. Magnified 100 diameters.

as seen with the microscope are very sharp. It is only possible to get a few in focus at one time to photograph. Outward from these crystals is a clear ring bordered by a transitional cloudy zone grading into the opaque ring. This ring is in turn surrounded by a clear ring and the whole inclosed in opaque jasper. The crystals are interpreted as having been formed by a segregation of iron oxide from the now clear nucleus while the whole was in a gelatinous state.

The manganiferous portion of the chert from the same locality is seen in thin section to consist of a breccia of two sorts of chert. The matrix is chert containing numerous minute cracks with filled manganese oxides which give a dark color to the whole, and the fragments are clear silica whose margins appear to have been slightly stained with manganese. In these stained portions botryoidal

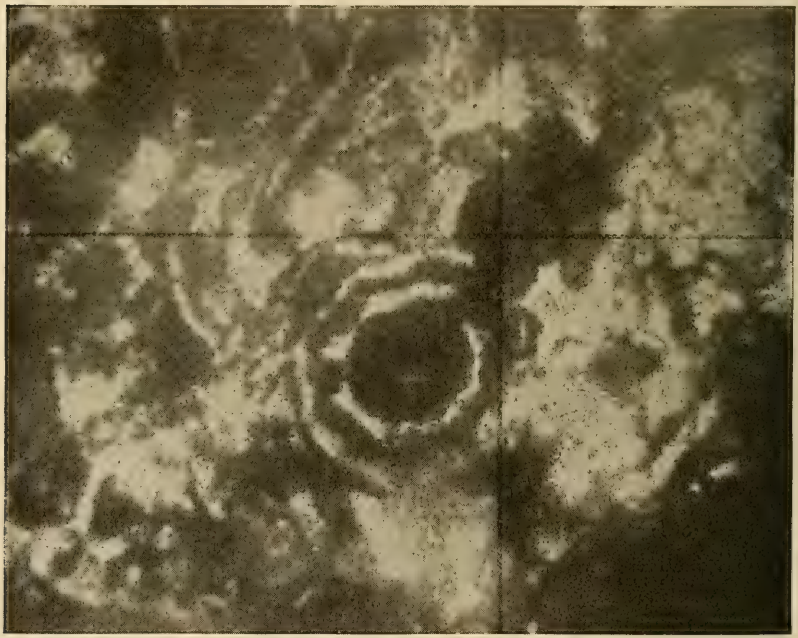

FIG. 3.—From same field as Figure 2. Shows detail of banding and dust of iron oxide included in clearer silica areas. Magnified 370 diameters.

and spherical structures are seen, both showing a faint radial arrangement of the constituent silica. In places in the clear silica fragments manganese oxides fill small irregular cracks several of which radiate from a common point and appear to indicate shrinkage.

Jasper from the interstices of the pillows on the first point west from Deepwater Point of the Northwest Arm of Fortune Harbor shows a structure very similar to that which is illustrated in Figure 2.

ORIGIN

COMPARISON WITH OTHER REGIONS

Before taking up the origin of the cherts, it will be well to compare them to similar formations elsewhere. In reading the literature of this subject, one cannot but be greatly impressed by the abundance of chert formations which are similar in many respects to those of Notre Dame Bay. Such formations have a

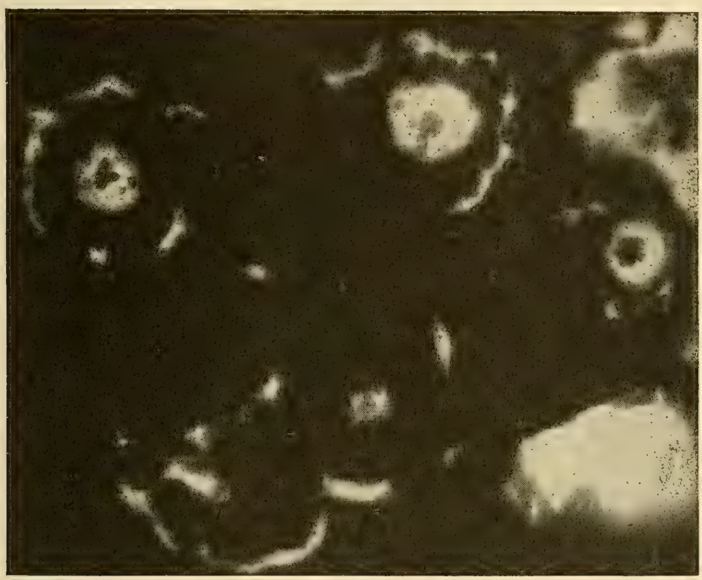

FIG. 4.—From same thin section as Figures 2 and 3. Show segregation of iron oxide into hematite plates and also original banding outside the area of segregation. Magnified 430 diameters.

very wide distribution both in area and in geologic time. E. F. Davis[1] has recently given a thorough review of the literature describing the types of chert here under discussion so that any extended review here is unnecessary. A most strikingly uniform feature of the descriptions is the intimate association with volcanic rocks. Pillow lavas usually form a part of the section, although, as in Notre Dame Bay, the chert itself is usually interbedded with shale or tuff. The following will serve as examples.

[1] E. F. Davis, "The Radiolarian Cherts of the Franciscan Group," *Bull. Univ. Calif.*, Vol. XI (1918), No. 3, pp. 235–432.

In eastern Australia is found a thick series of Devonian rocks. They form a belt extending from Tamworth to Bingara. According to David and Pittman[1] they consist principally of "clay-stones" with numerous interstratified bands of submarine tuff. There are a few limestone beds, one being 50 to 100 feet thick, and others only from 6 to 12 inches in thickness. Near Bingara and Barraba are exposed "several hundred feet of dark red-grey or greyish-white jasperoid rock" which is thin-bedded. Most of these rocks, including the limestone, are replete with radiolaria.

Near Tamworth the chert is found only in small quantities. Here there are many beds of tuff interbedded with the shale, large sections showing beds of shale alternating with the tuffs. "The shales sometimes pass into chert in contact with tuffs and cherty masses occur inclosed within the tuff beds."[2] In places there is an extraordinarily intimate mixture of chert with tuff, the chert occurring in disconnected areas of extreme irregularity.[3]

Radiolaria are found in all types of rock, cherts, shales, tuffs, and limestones, the latter yielding extremely well-preserved forms. At many places Lepidodendron remains are abundant in the shales indicating that the sediments were laid down near shore.

Analyses of various types of rock are given and in discussing these the authors say:

> With reference to these analyses, we could comment on the fact that although, so far as can be judged from the microscopic examination, the radiolarian shales are almost as rich in radiolarian remains as the black chert, the former contain only about 68 per cent of silica, while the latter contain 91.06. This points, in our opinion, to the probability that the higher percentage of silica in the chert is due, not to the silica it has received from the radiolarian tests, but rather to secondary silica derived from the siliceous tuffs.

Since the work of David and Pittman, Benson[4] has found that spilitic lava flows occur in various parts of the section. He believes that they are submarine flows and cites one instance where the lava contains coral fragments.

[1] T. W. E. David, and E. F. Pittman, "On the Paleozoic Radiolarian Rocks of New South Wales," *Quar. Jour. Geol. Soc.*, Vol. LV (1899), pp. 16–37.

[2] *Ibid.*, p. 27. [3] *Ibid.*, figure on p. 22.

[4] N. Benson, "Spilite Lavas and Radiolarian Rocks of New South Wales," *Geol. Mag.*, Decade V, Vol. X (1913), pp. 17–21.

In the southwestern part of the Kenai Peninsula, Alaska,[1] chert is found in three formations of Triassic age. The rocks are exposed on the southeast shore of Kachemak Bay, and on portions of the shore to the south.

The oldest series is composed largely of pillow lavas. It probably has a thickness of about 3,000 feet, and throughout this thickness pillow structure is well developed. In nearly every section of these rocks chert is found forming beds as much as 40 to 50 feet thick. There are in places a few thin beds of tuffs.

Younger than these pillow lavas, which cannot be referred to the Triassic with absolute certainty, is a series of rocks composed largely of thin-bedded chert. The areas of this formation as mapped "include numerous small undifferentiated masses of ellipsoidal lavas, the two kinds of rock being so intimately and complexly associated as not in all places to permit an accurate cartographic separation of the smaller areas of lava." The relations of the lava to the cherts are believed to be due in part to consecutive deposition, and in part to contiguity due to faulting.

> The cherts are everywhere intensely deformed, minute crumpling being universal and faulting being common, so that it is impossible to make even the roughest estimate of the thickness of the formation, nor can any upper and lower part be determined in any local section. . . . .
>
> The cherts are thin-bedded and even bedded rocks consisting of hard siliceous layers from half an inch to 2 inches thick, separated by thin films of softer material. The hard siliceous layers are of fairly uniform appearance except as they vary in color. They are of very fine grain, being uniformly of almost glassy texture and not containing any recognizable detrital fragments. The character of the material between the hard siliceous beds was not definitely determined, but is probably shaly. The color of the chert at most places is green, grey, or black. Brown or red cherts were noted at a few places, and are believed to owe their color to the infiltration of iron minerals. . . . .
>
> The cherts show in thin section a fine-grained siliceous groundmass containing no indication of detrital grain, but contain rounded forms which suggest the simpler Radiolaria.[2]

There is also a series of limestones whose exact relation to these other rocks is not known. They are found in the vicinity of Port

[1] G. C. Martin, B. L. Johnson, and U. S. Grant, "Geology and Mineral Resources of the Kenai Peninsula, Alaska," *Bull. U.S. Geol. Survey*, No. 587, 1915.

[2] *Ibid.*, pp. 60–61.

Graham. This series which may be about 500 feet thick contains occasional beds of tuff, tuffaceous conglomerates, and breccias. There are in the section beds of massive black chert which may be interbedded with the tuffs.

The radiolarian cherts of the Franciscan Group are unique in some respects. They have been fully described by Davis.[1] The Franciscan Group over about 1,000 miles of the Coast Ranges of California and Oregon and in the Olympic Mountains of Washington. The group shows great lithological uniformity throughout. It consists of a thick series of arkose sandstones, radiolarian cherts, and foraminiferal limestones, with subordinate shale and conglomerate. Pillow basalts and diabases are common. Some of them are believed to be intrusive. In the vicinity of San Francisco Bay there are two heavy formations of chert of 530 and 900 feet in thickness. Besides these persistent formations there are many small isolated lenses of chert, some of them outcropping over several acres. The bedding in even the thickest of these formations is exceedingly irregular, individual beds showing pinchings, swellings, and lens-like forms which are compensated for by the adjacent beds.

The radiolarian cherts of the British Isles are particularly interesting in connection with the present investigation. These cherts not only have an association almost identical to that of many of the Notre Dame Bay cherts, but some of them are contemporaneous. Moreover where fossils have been found in Notre Dame Bay they are of types so nearly identical with those of Great Britain as to imply a connection or some means of migration between the two regions.

On Mullion Island,[2] off the southwest coast of Cornwall, occur radiolarian cherts which are probably of Ordovician age, perhaps Lower Ordovician. Chert is here closely associated with pillow basalt and is found in a series of shales and limestones which are underlain and overlain by igneous rocks. The chert is interstratified with shale and occurs in bands which vary in thickness

[1] E. F. Davis, *op. cit.*, pp. 235–432.

[2] H. Fox and J. J. H. Teall, "On a Radiolarian Chert from Mullion Island," *Quar. Jour. Geol. Soc.*, Vol. XLIX (1893), pp. 211–20.

from one quarter of an inch to several inches. As many as thirty bands have been counted within three feet. The bedding of the chert is somewhat irregular, and this the authors ascribe to motion before its consolidation.

Even more striking are the Ordovician radilaria-bearing cherts of southern Scotland.[1] A continuous belt of Ordovician and Silurian rocks some 40 miles in width extends across the Southern Highlands of Scotland from coast to coast. The Ordovician rocks are best exposed in the northern part of this belt, particularly at the western extreme in the Girvan area. The lowest Ordovician is represented by a series of volcanics consisting of agglomerates, tuffs, and lava flows showing pillow structure to great perfection. In places a little chert is associated with the uppermost pillow lavas. These are overlain by a few feet of black graptolitic shale which fixes their age. Succeeding these is a series of radiolarian cherts and "mudstones," some 70 feet in thickness, which occurs sporadically over an area of about 2,000 square miles. The cherts are often interbedded with tuffs. The bedding is irregular, and in places a bed of chert may have a botryoidal upper surface. Concerning the cherts of the Girvan area the authors say:

> The volcanic series passes upwards into red, green, and gray cherts which are interstratified with tuffs and breccias that clearly overlie the Middle Arenig band of black shales. Indeed the cliff sections leave no room for doubt that the radiolarian cherts were deposited contemporaneously with the volcanic eruptions, for not only are they intercalated with the breccias, but the latter likewise contain fragments of organic chert with radiolaria, which must have solidified on the sea floor before its disruption by the explosion.[2]

The authors, following Hinde, regard these cherts as radiolarian oozes.

The Middle Ordovician or Llandeilo is conformable with the Arenig. It consists of cherts and "mudstones" with some interbedded tuffs and breccias. "In a few exceptional localities [in the northern part of the belt] the cherts are apparently intercalated with graywackes in such a way as to preclude the supposition that the relationship is due to faulting," which would indicate that if

[1] B. N. Peach and J. Horne, *The Silurian Rocks of Britain*, Vol. I, Mem. Geol. Surv. United Kingdom, 1899.

[2] *Ibid.*, p. 40.

the cherts be accumulations of radiolarian tests they can hardly be considered as oozes.

Vulcanism continued to a moderate degree into the Caradoc, but, as in Notre Dame Bay, cherts are not found in the rocks of this age. The geological history of the two regions is strikingly similar.

These examples, which might be multiplied, serve to show the wide distribution of cherts associated with volcanic rocks, and it is believed that in some instances, where volcanic rocks do not form part of the chert-bearing sections, vulcanism may have been nearly contemporaneous with the chert formation without its products appearing with the cherts. An example of such conditions is seen in the chert-bearing sections in Badger Bay of Notre Dame Bay.

Are Cherts Radiolarian Oozes?

G. J. Hinde, the foremost student of the radiolaria, regarded radiolarian cherts as lithified oozes, and continually used the presence of radiolaria as a criterion for determining the deep water origin of the rocks containing them. That the cherts are deep water deposits has often been questioned, due to the common association with black graptolitic shale, and to the occasional association with sandstones.

That the radiolarian cherts of the Franciscan Group were not deposited in extremely deep water has been shown by E. F. Davis. He says:

> The Franciscan sandstone [the principal member of the Franciscan Group] is a medium, coarse-grained sandstone which appears to be, in large part, of continental origin. None of it was laid down far below sea level. In the neighborhood of San Francisco, there are two formations of radiolarian chert which divide the sandstone into three formations. If we regard the cherts as abyssal radiolarian oozes, like those of the present day, we must believe that the region sank from sea level to a depth of from 12,000 to 15,000 feet, and that this tremendous displacement occurred twice within Franciscan time, with two reversals of movement.[1]

The association of some of the radiolarian cherts of southern Scotland with greywackes has already been noted (pp. 16–17).

[1] *Op. cit.*, p. 362.

In Notre Dame Bay the rock containing the most abundant radiolaria is not a chert but is the red shale of the islands south of Gull Island in Badger Bay.

In other occurrences of radiolarian cherts it seems that the only criterion employed for determining the abyssal origin was the presence of the radiolaria.

Have the Radiolaria Played an Active Part in the Formation of the Chert?

This question has often been raised in regard to the radiolarian cherts. It was at first answered in the affirmative, but some of the more recent investigators are inclined to the opposite opinion.

Concerning Franciscan cherts Lawson says:

> As regards the organic origin of the silica of which the chert is composed, it seems to the writer that there are features both in the slides and in the field occurrence of the formation which do not harmonize with this supposition. In the slides having the radiolarian remains, the latter generally occur as casts of forms imbedded in a matrix of silica which shows no evidence whatever of volcanic origin. The cavities of the radiolaria have been filled with chalcedonic silica, and are in definite contrast with the nonchalcedonic matrix. The discrete character of the fossils is significant of their mode of accumulation. The silica seems to have been an amorphous chemical precipitate, forming in the bottom of the ocean in which the radiolaria thrived. The dead radiolaria dropped into this precipitate, became imbedded in it, and were so preserved.[1]

Davis also holds that the radiolaria of the Franciscan cherts are merely incidental fossils which were imbedded in gelatinous silica.

In Notre Dame Bay some of the best preserved radiolaria occur in jasper. In sections of this the radiolaria appear as clear areas, sometimes showing an opaque center. The boundaries are often exceedingly sharp. The areas are composed of quartz which is relatively coarse-grained. Where radiolaria are observed in green cherts some of the silica of the chert may be amorphous. In neither case is there evidence that the rock in which the preserved radiolaria are imbedded can be in any way made up of radiolarian remains.

[1] A. C. Lawson, "Sketch of the Geology of the San Francisco Peninsula," *15th Ann. Rept., U.S. Geol. Surv.* (1895), pp. 424–25.

In this connection may be mentioned the radiolaria-free chert occurring between the interstices of pillows both in Notre Dame Bay and in pre-Cambrian areas of the Lake Superior district and on the east side of Hudson Bay.

Cherts Formed as Chemical Precipitates

The field relations and the structure as revealed by thin sections give evidence that the cherts are chemical precipitates. As to the field relations, Van Hise and Leith, in their study of the original iron-bearing formations of the Lake Superior region, have used a criterion which may be applied with equal force to the sedimentary cherts of Notre Dame Bay. This has been summarized by Leith as follows:

> The sharp contacts of iron formation rocks, the great thickness and general lack of contained chemical detritus in the iron formation, notwithstanding its association with chemical deposits, leads us to believe that the deposition of the iron formation sediments began suddenly and went on rapidly. It is not easy to conceive of the total inhibition of the deposition of fragmental sediments during this time, but relative rapidity of the deposition of the iron salts would mask the fragmental deposition. This rapidity of deposition would be more in accord with the hypothesis of rapid direct contribution of iron salts following igneous outbreak than their more slow accumulation through normal erosion processes of igneous rocks, and especially does this seem likely to be true where the iron formations completely lack associated fragmental material and are bounded both above and below by ellipsoidal flows.[1]

The silica of the cherts is very fine-grained, generally microcrystalline. In some sections there are areas in which exceedingly fine specks of faintly birefringent silica occur in an amorphous base. The occurrence of this amorphous silica is consistent with the theory that the cherts are chemical precipitates, and, as it is present in sections which show distinct radiolarian remains, it is difficult to explain as being formed of comminuted radiolarian tests.

The evidence is clear that the chert of two previously described localities at Fortune Harbor has been in a gelatinous condition. Both the jasper from the interstices between the pillows on the Northwest Arm (p. 584) and that from the heavy bed at the manganese prospect on the Southwest Arm (p. 583) show concentric rings

[1] C. K. Leith, *Lake Superior Type of Iron Ore Deposits*, in *Types of Ore Deposits*, edited by H. F. Bain, San Francisco, 1911, p. 75.

of iron-rich bands and pure silica, and the outlines of the grains of quartz of which the rock is now composed are entirely independent of this banding. Also, segregation of iron oxide into aggregates of hematite plates, the aggregate bordered by clear silica, must have taken place when the silica was in a gelatinous condition. The occasional occurrence of radiating chalcedony about these aggregates supports this view.

In connection with the concentric structures referred to above may be mentioned again the botryoidal upper surfaces of some Ordovician cherts of southern Scotland (p. 589).

Source of the Solutions

Since the conditions under which the cherts of Notre Dame Bay were formed are believed to be much the same as those under which some of the iron-bearing formations of the Lake Superior district were formed, it is of interest to examine the views of the workers in this field as to the source of the solutions. Van Hise and Leith[1] consider two sources of solutions which would produce a chemical precipitate. The first is a direct emanation from a submarine effusive. This emanation they believe to have carried a ferrous iron salt, probably the sulphate, and silicates of the alkalies. The second source of the active solutions is the reaction of the molten rock with sea water, and experiments were conducted to test the efficacy of this process. "Fresh basalts were heated in a muffle furnace to a temperature of 1,200° C., a temperature sufficient to fuse the exterior, and then plunged into salt water of the composition of sea water, the result being a violent reaction, producing principally sodium silicate but also bringing a small amount of iron into solution."[2]

The work of Dewey and Fleet[3] has an important bearing on this subject. They describe the pillow lavas of Cornwall and Devon. A peculiar feature of these rocks is that their feldspars have been extensively altered to albite, and it is shown that this took place

[1] C. R. Van Hise and C. K. Leith, "Geology of the Lake Superior Region," *Mon. No. 52, U.S. Geol. Survey.*

[2] *Ibid.*, p. 516.

[3] H. Dewey and J. S. Fleet, "On Some British Pillow-Lavas and the Rocks Associated with Them," *Geol. Mag.*, New Ser., Decade V, Vol. VIII, pp. 202–9 and 241–48.

at an early period, probably immediately after eruption. They believe that "The igneous rocks as they cooled down exhaled vapors or solutions of magmatic origin, rich in dissolved silicates of soda and other bases. These were the agencies which albitized and decomposed the lava, and any excess must have escaped into the sea water."[1] With these pillow lavas are associated cherts which carry radiolaria and the authors believe that the cherts were formed by the accumulation of their remains, pointing out that such siliceous waters would be particularly favorable to their growth.

Lawson has proposed[2] still another source for the siliceous waters from which he believes the Franciscan cherts were deposited. These cherts are not so intimately associated with volcanic rocks as are the cherts of many other regions, but pillow lavas are present in the Franciscan group. However, the evidence that these cherts have been in a gelatinous state is unusually clear, thin sections showing much isotropic silica and spherules of chalcedony. Moreover the field relations of these rocks are peculiar. "Most of the individual occurrences . . . . are of very limited extent, occupying only a few acres, or only a fraction of an acre, and it seems impossible to conceive that they had any other than a very local origin."[3] Where thick beds are found the individual members are seen to be but lenses of very limited extent. The whole aspect of the occurrences is such as to suggest a very local origin, and Lawson has proposed the theory that they are deposits from siliceous springs.

We may conclude, concerning the cherts of Notre Dame Bay, that their intimate association with volcanic rocks, as is so generally the case, indicates a genetic connection. The writer believes that they are chemical precipitates. The bedding of the sedimentary cherts is so uniform that they cannot have had such a very local origin as the Franciscan cherts. The widespread pillow lavas, usually forming part of chert-bearing sections, are considered of submarine origin. The tuffs associated with the cherts show no evidence of shallow water origin, such as ripple marks or cross bedding;

[1] *Ibid.*, p. 245.

[2] A. C. Lawson, "Sketch of the Geology of the San Francisco Peninsula," *15th Ann. Rept., U.S. Geol. Survey*, pp. 399–476.

[3] E. F. Davis, *op. cit.*, p. 245.

and other shallow water and subaerial sediments, so common in the younger formations of the district, are completely lacking. May not, then, the centers from which these tuffs were erupted have been submarine, at least in the early stages of their development? If this were the case, there cannot but have been a great contribution of magmatic waters to the basin in which the cherts were deposited.

Flows of such extent as the pillow lavas of Notre Dame Bay are generally conceded to be of fissure type, and from this source also siliceous solutions would emanate.

To a small degree siliceous solutions may have been formed by the reaction of molten rock with sea water. This would be particularly effective in the case of the pillow flows and may account for some of the silica of the chert which occurs between the pillows and which forms but a very small proportion of the whole aggregate.

Nature of Solutions and Manner of Precipitation

Some of the processes held to be effective in the precipitation of siliceous sediments may profitably be reviewed.

Van Hise and Leith have suggested the direct chemical precipitation of some of the jasper of the Lake Superior region. In their experimental work on the origin of greenalite and ferrugenous chert, they showed[1] that greenalite ($FeSiO_3$) may be formed by the reaction of a ferrous iron salt with sodium silicate as follows:

$$FeSO_4 + Na_2O.3SiO_2 = FeO.3SiO_2 + Na_2SO_4$$

and they showed that the precipitate $FeO.3SiO_2$ consists of a ferrous silicate and silica, and that the proportions of these will depend on the relative amounts of the iron salt and water glass used.

Although most of the chert of the Lake Superior region is secondary after greenalite, which may be observed in all stages of alteration to chert, they say:

> Certain facts have been described for the Keewatin iron formations indicating that the present hematitic and magnetic jaspers may not be the result of alteration of earlier ferrous compounds, but are original precipitates in the

[1] *Op. cit.*, pp. 521–22.

present form. The same kinds of solutions from these igneous rocks being postulated as seem to be required to produce greenalite and carbonate.[1]

They do not go into the details of the process of formation of the silica of the jaspers.

Davis, following Lawson, believes that the solutions which were responsible for the cherts of the Franciscan formation were derived from springs.

It is possible that a solution of silicic acid might diffuse through a fine mud on the sea floor and that the silicic acid should be precipitated throughout the mud in regular layers, thus producing the rhythmic bedding.

Perhaps a fine mud was permeated with a solution of silicic acid or some silicate, and by the diffusion of some other substance into it, ... a regular rhythmic banding was brought about.[2]

Davis performed some experiments with suspensions of clay which indicate "that silicic acid possesses the ability to free itself from mechanical impurities and that it can do so in a rhythmic manner." Thus Davis would explain the laminations of the Franciscan cherts.

Cox, Dean, and Gottschalk[3] in their work on the chert associated with the zinc ores of southwestern Missouri have thrown much light on the chemistry of silica in nature. Although their conclusions are applied to chert occurring in limestone, yet the fundamental processes which they discuss are applicable to the siliceous sediments of Notre Dame Bay.

In brief, they conclude that the silica existed in solution in ground water in the form of a colloid. This colloid they believe to have been precipitated by Ca^{++} ions formed by the disassociation of $Ca(HCO_3)_2$ which was in turn formed by the action of carbonated waters on limestone. They also indicate the possibility of some silica, as in petrified wood, being formed by the coagulative effect of positively charged colloids.

Kahlenberg and Lincoln[4] long ago investigated the nature of silica in dilute solutions. They showed that such salts as sodium

[1] *Ibid.*, p. 527.

[2] E. F. Davis, *op. cit.*, p. 401.

[3] G. H. Cox, R. S. Dean, and V. H. Gottschalk, "Studies of the Origin of Missouri Cherts and Zinc Ores," *Bull. Univ. Missouri School of Mines and Met.*, Vol. III, No. 2, 1916.

[4] Louis Kahlenberg and A. L. Lincoln, "Solutions of Silicates of the Alkalies," *Jour. Phys. Chem.*, Vol. III (1898), pp. 77–99.

silicate dissociate and yield colloidal silica. Clarke[1] in reviewing their work concludes, "in natural waters, then, silica is actually present in the colloidal state, and not in acid ions."

That silica is flocculated or precipitated by ocean water is clearly shown by its absence in the ocean water and its abundance in river water. Precipitation in this case is clearly brought about by the action of electrolites. If magmatic waters were discharged into ocean water this action would surely prove effective.

Tarr has suggested[2] a similar method of coagulation for the origin of some syngenetic chert nodules, assuming that the silica was carried into the sea by rivers. Dean[3] in criticizing this theory says:

> If, however, the silica is precipitated by the salts of the sea, these salts, or at least their cations, should be the principal material to be absorbed by silica and would hence form the principal impurity in the chert. Since sodium chloride is the salt present in largest amount in the sea water, we should expect to find a predominance of sodium in the chert; as a matter of fact, the analyses show very little sodium and a decided predominance of calcium and magnesium carbonates.[4]

In answer to this criticism it seems doubtful to the present writer if the concentration of alkalies in sea water as compared to the concentration of the alkaline earths is sufficiently high (7.3:1) to greatly overbalance the far greater coagulative power of the bivalent ions. The analysis on page 580 shows 1.04 per cent of alkalies and .73 per cent of alkali earths in molecular ratio $Na+K:Mg+Ca::1.6:1$. The absolute figures and the ratio appear to the writer not inconsistent with theory of coagulation by electrolites. The abundance of K is perhaps to be explained by the displacement of adsorbed Na.

It seems reasonable to suppose that the magmatic waters derived from the same sources as the volcanics of Notre Dame Bay would

[1] F. W. Clarke, "The Data of Geochemistry," *U.S. Geol. Survey Bull. 616*, 1916, p. 194.

[2] W. A. Tarr, "Origin of Chert in the Burlington Limestone," *Am. Jour. Sci.*, 4th ser., Vol. XLIV (1917), pp. 409–52; "Oolites in Shale and Their Origin," *Bull. Geol. Soc. Am.*, Vol. XXIX (1918), pp. 587–600.

[3] S. Dean, "The Formation of the Missouri Cherts," *Am. Jour. Sci.*, 4th ser. Vol. XLV (1918), pp. 411–15.

[4] *Ibid.*, p. 412.

contain considerable ferrous iron. When such a solution was mixed with ocean water the iron would become oxidized and by hydrolysis ferric hydroxide would form. The iron now present in the jaspers as hematite may have been precipitated in this way. This colloidal ferric hydroxide which carries a positive charge would then be an agent which might coagulate colloidal silica and this action would be mutual.

A third process, probably of minor importance, may have been effective in the formation of the chert sediment. Van Hise and Leith, as stated above, showed that a ferrous salt will react with water glass to form ferrous silicate, silica, and a sodium salt. The ferrous silicate had the properties of greenalite. Some such reaction has very likely taken place as evidenced by the analysis of green chert which indicates the presence of both ferrous and ferric iron, and as evidenced by the occurrence of minute particles resembling thuringite in the specimen analyzed and in many others.

The danger is realized of trying to explain the exact mechanism of the chemical processes in the formation of the cherts. However, the suggestions offered above indicate methods capable of producing the materials from which the rocks could be formed. The main purpose of this paper is to call attention to the widespread occurrence of chert with marine volcanic rocks and to endeavor to establish the fact of their inorganic chemical origin.[1]

[1] Since this paper was written the paper of Gruner on the highly ferruginous cherts of the Lake Superior region has been published (*Econ. Geol.*, Vol. XVII (1922), pp. 407–60. Gruner attributes to the action of bacteria and algae the principal rôle in the precipitation of both the silica and the iron. The materials are thought to have been brought into solution largely by the weathering of volcanic rocks made more active by organic acids formed by the decay of primitive vegetal organisms. He also considers the reaction of volcanic submarine flows with water and the direct contribution of magmatic water to marine basin. Both of these sources of material he believes to be less important than by weathering products. Magmatic solutions he particularly dismisses as inadequate. Space does not permit such a discussion as the paper warrants. The present author feels, however, that there is no evidence presented which requires a change in view as to the origin of the chert of Notre Dame Bay. He has re-examined the thin sections in hope of finding some minute organisms which might have been overlooked. None were found. He believes that, if they were found, proof would be required that they were not incidental fossils as are the radiolaria.

TO QUESTION THE THEORY OF PERIODIC DIASTROPHISM

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Periodic diastrophism as it is understood by T. C. Chamberlin, R. T. Chamberlin, Schuchert, Willis, and most other writers, does not mean that diastrophism has only been locally periodic, but that periodicity has been world wide. The writer has no desire to attack the well-established idea of peneplanation and relative quiescence locally over long periods, but rather to challenge such statements as: "the earth has passed through periods of diastrophic activity alternating with periods of relative quiescence,"[1] and to replace this idea with the suggestion, that diastrophism has been continuous and that the crust has been constantly shortening to fit itself to a shrinking interior. Among American geologists the theory of periodic diastrophism is generally accepted, so that it is no small undertaking to attempt its overthrow. However, it seems to be of vital importance to a knowledge of the causes and modes of deformation of the earth's crust to know whether such deformation is continuous or intermittent. Also attempts to correlate geological time by diastrophism have been made. At least the subject should be critically examined.

In the present article periodic diastrophism will be considered from three points of view. First, a brief examination of the times of diastrophism will be made to see where the gaps, if there are any such, occur in the diastrophic record. Secondly, the apparent concentration of diastrophism at a few times during the geological history will be considered. Thirdly, the idea of accumulation of strains within the earth over long periods before yielding will be questioned.

THE GEOLOGICAL RECORD OF DIASTROPHISM

Since the conception of periodic diastrophism is based primarily on field observations, some consideration of the evidence offered by these will be made. The accompanying table has been compiled

[1] R. T. Chamberlin, "Periodicity of Paleozoic Diastrophism," *Jour. of Geol.*, Vol. XXII, p. 315.

TABLE SHOWING TIMES OF DIASTROPHIC MOVEMENTS

Geol. Time	Locality	Time Limits	Importance	References
Present	Dutch East Indies	Post-Pleistocene	Moderate	H. A. Brouwer, *Jour. of Washington Acad. of Sci.*, Vol. XII, p. 181
Pleistocene	California	Post-Pliocene during and after Saugus epoch	Great	B. L. Clark, *Jour. of Geol.*, Vol. XXIX, pp. 613–14
Pliocene and Pleistocene	Himalayas	Coarse Pliocene. Congolmerates are folded. Recent covering	Very great	R. D. Oldham, Geol. Survey, India, *Geology of India*, 2d ed., pp. 477–87
End of Pliocene	California	Post-Pliocene. Pre-Saugus	Fairly great	B. L. Clark, *op. cit.*, p. 608
Pliocene	Greater Antilles	Post-Miocene. Pre-Pleistocene	Moderate	Stephen Taber, *Jour. of Geol.*, Vol. XXX, p. 89
Early Pliocene	Caucasus Range	Post-Miocene	Great	W. B. Scott, *An Introduction to Geology*, p. 754
End of Miocene	San Francisco Region	Post-Upper Miocene. Pre-Lower Pliocene	Moderate	B. L. Clark, *op. cit.*, p. 607
Mid Miocene	Pacific Coast	Post-Lower Miocene. Pre-Upper Miocene	Great	Eliot Blackwelder, *Jour. of Geol.*, Vol. XXIV, pp. 647–48
Throughout Miocene	Alps		Great	Marcel Bertrand, *Bull. Soc. Geologique de France*, 3d ser., Vol. XV, p. 434
End of Oligocene	California Coast Range	Post-Upper Oligocene. Pre-Lower Miocene	Moderate	Ralph Arnold, *Jour. of Geol.*, Vol. XVII, p. 520
Late Oligocene	Corsica	Post-Oligocene. Pre-Lower Miocene	Moderate	Eugene Maury, *Bull. Geol. Soc. de France*, 4th ser., Vol. X, p. 290
Oligocene	Alps	Pre-Lower Miocene	Fairly important	Emile Haug, *Traité de Géologie*, II (1911), 1736
Early Oligocene or late Eocene	Colorado	Post-Bridger	Moderate	R. C. Hill, *U.S. Geol. Survey, Walsenburg Folio*, p. 2
Late Eocene and early Oligocene	Pyrenees Spain	Between mid-Eocene and late Oligocene	Important	Emile Haug, *op. cit.*, p. 1572
Middle Eocene	Alaska and parts of Rockies	Post-Lower Eocene. Pre-Neocene	Great	Brooks and Prindle, *Prof. Paper 70, U.S. Geol. Survey*, 1911, p. 117. Rowe and Wilson, *Univ. of Montana Bull.* 4, p. 62, and others
Early Eocene and Latest Cretaceous	Rocky Mountains	After Laramie, etc. Pre-Wasatch, etc.	Very great	Most Rocky Mountain Folios of the U.S. Geol. Survey and many other citations
Late Cretaceous	Western Alps	Base of Maestrichten	Moderate	Emile Haug, *op. cit.*, p. 1127
Middle Cretaceous	Pacific Coast	Post-Comanchean. Pre-Upper Cretaceous	Moderate	Eliot Blackwelder, *op. cit.*, pp. 645–46
Lower Cretaceous	New Zealand		Great	Benson, *Jour. of Geol.*, Vol. XXX, p. 6
Late Jurassic	Basin and Pacific Ranges		Great	Eliot Blackwelder, *op. cit.*, pp. 643–45
Mid Jurassic	Crimea	Post-Lower Jurassic. Pre-Upper Jurassic	Fairly important	Emile Haug, *op. cit.*, p. 1127

TABLE SHOWING TIMES OF DIASTROPHIC MOVEMENTS—*Continued*

Geol. Time	Locality	Time Limits	Importance	References
Late Triassic or early Jurassic	Northeastern United States	Post-Newark (Late Triassic)	Moderate	Pirsson and Schuchert, *Textbook of Geology*, 1915 ed., p. 820
Mid Triassic	South Africa	Post-Lowest Triassic	Slight	Ed. Suess, *The Face of the Earth*, Sollas Trans., Vol. IV, p. 102
Early Triassic	Donetz basin Russia	Post-Upper Permian. Pre-Jurassic	Moderate	Emile Haug, *op. cit.*, p. 834
Late Permian and probably partly Triassic	Appalachian Mountains	Post-Lower Permian. Pre-Late Triassic	Important	David White, *Bull. Geol. Soc. America*, Vol. XIV (1903), pp. 538–42, and many others
Lower Permian	Hercynian System Western Europe		Great	Emile Haug, *op. cit.*, pp. 917–18
Late Pennsylvanian	Hercynian System	Westphalian below, Stephanian above	Great	Emanuel Kayser, *Geologische Formationskunde*, 2d ed., p. 174
Middle Pennsylvanian	Arbuckle Mountains	Post-Mississippian. Pre-Uppermost Pennsylvanian	Moderate	J. A. Taff, *Prof. Paper 31, U.S. Geol. Survey*, p. 38
End of Mississippian	Arbuckle Mountains	Post-Mississippian. Carboniferous conglomerates above	Moderate	*Ibid.*, p. 37
Mississippian	Australia	Post-Upper Devonian Great erosion before Permo-Carboniferous	Fairly great	C. A. Sussmilch, *Geology of New South Wales*, 2d ed. (1914), p. 81
End of Devonian	Ancestral Ranges of Europe	Post-Devonian. Pre-Lower Carboniferous	Fairly great	Emile Haug, *op. cit.*, p. 831
Late Devonian	Northeast United States	Post-Hamilton. Pre-Uppermost Devonian	Fairly great	R. T. Chamberlin, *Jour. of Geol.*, Vol. XXII, pp. 330–31. J. M. Clarke, *Mem. New York Mus. No. 9* (1908), pp. 14–15
Lower or Mid Devonian	Alaska	Post-Silurian. Pre-Uppermost Devonian	Moderate	W. C. Mendenhall, *Prof. Paper 41, U.S. Geol. Survey*, p. 76
Beginning of Devonian	Caledonian Mountains, Wales		Moderate	Jukes-Browne, *Building of the British Isles* (1911), p. 114
End of Silurian	Caledonian Mountains, Scotland, and Scandinavia		Great	Ed. Suess, *op. cit.*, Vol. II, pp. 82–86, 386–89
Upper Mid Silurian	Spitzbergen	Post-Silurian undif. Pre-Uppermost Silurian	Moderate	Olaf Holtdahl (cited by R. T. Chamberlin, *op. cit.*, p. 328)
Early Mid Silurian	British Isles	Post-Lower Silurian. Pre-Upper Silurian	Moderate	A. C. Ramsay, *Physical Geog. and Geol. of Great Britain*, 6th ed. (1894), p. 74
End of Ordovician	Australia	Post-Ordovician. Pre-Silurian	Great	C. A. Sussmilch, *op. cit.*, p. 18
Late Ordovician	Appalachian region	Began pre-Richmond, probably continued into Silurian	Great	E. O. Ulrich, *Bull. Geol. Soc. Am.*, XXII (1911), pp. 436–37

to show the almost continuous record of orogenic diastrophism since the beginning of the Paleozoic. In compiling the table, pre-Cambrian diastrophic movements are not mentioned because of the great uncertainty as to the exact time of their occurrence. The table includes only a list of the most important disturbances which occurred in the different subdivisions. Several assumptions were made in compiling the table. The time of diastrophism was supposed not to be a point of time, but to have extended over a considerable fraction of a period, let us say on the average about a third of a period. This may sound arbitrary, since the length of the periods vary, but probably no harm was done in making such an assumption, because it is becoming well recognized that orogeny is not as brief a process as it was formerly considered. The orogenic disturbances in the table which are in italics were located definitely in a fraction of a period or near the juncture of two periods by taking into consideration the youngest disturbed beds and the first beds deposited after the disturbance. Since by considering these deformations alone, certain gaps were left, other orogenic disturbances the time basis of which were more open to question were used in the table. These last depend generally on the statements of reliable geologists which do not include the complete stratigraphic evidence. It can hardly be expected that the location of all these deformations will meet the requirements of everyone.

While the great warpings, which alternately submerge and emerge much of the continents, are of course considered diastrophic movements, their relation to the shortening of the earth's crust has been questioned by many. Therefore the table will not make mention of this type of deformation.

Examination of the table leads one to wonder where the great world-wide periods of quiet come in, unless they are all pre-Ordovician. While the list probably contains inaccuracies, it seems likely that there has been no time in the history of the earth, at least since the Ordovician, when there has been an absence of important orogenic movements.

PERIODIC CONCENTRATION OF DIASTROPHISM

Probably the question will have presented itself to some readers as to the possibility that diastrophism might have been continuously

active to a moderate degree, but very much concentrated at certain times. While there seems to be very little evidence that such has been the case in the Cenozoic, there is some evidence for it in the Paleozoic and perhaps in the Mesozoic. Most authors of textbooks and many other geologists speak of the end of the Paleozoic and the end of the Cretaceous as being times of very great disturbances all over the world. The end of the Ordovician, the end of Silurian, and the late Devonian are other times when diastrophism is said to have been more common than usual.[1]

In considering the probability of this type of periodicity, several points have to be borne in mind. In the first place, to have real evidence of periodicity, in each case there must be fossil-bearing horizons both directly above the unconformity and directly below. Such evidence is lacking in all but a few cases, as will be readily seen if the evidence for the times of deformation for these so-called epochs of great orogeny is examined. If the formation which is folded belongs to the next period, and if the exact horizon is unknown in each case, the deformation is generally referred with confidence to the end of the first period. If there is Silurian strata involved in folding and Devonian strata overlying the unconformity, provided that nothing is known about the exact age in either case, the deformation may have occurred well within the Silurian or even well within the Devonian period. If on the average an unconformity following mountain building represents a stratigraphic break of three-fourths of a period, the plotting of this extent of time will show that the faunas above and below the break represent different periods except when the center of the time break occurs within one-eighth of the center of the period. If the interval of the stratigraphic break is larger than this (and it generally is), the chances become still greater for discovering faunas of different periods above and below. Therefore, even if there is abundant evidence that diastrophism in many parts of the world occurred at the break in the stratigraphic record between periods, the diastrophism may have been distributed widely over the two periods.

Also, not infrequently, diastrophism is considered to have occurred directly after the close of a period when the evidence merely

[1] R. T. Chamberlin, *Jour. of Geol.*, Vol. XXXI, pp. 318–32.

shows either that the highest formations involved were located near the end of that period, or that the lowest formations not deformed belong to the next period, when the earlier record is missing. This practice is unfortunate, because the evidence merely indicates that the diastrophism occurred either after or before (as the case may be) the deposition of the beds in question and it may have occurred several periods later or previous.

R. T. Chamberlin's account of the Paleozoic disturbances[1] is very accurate and a most valuable contribution to geology, but the contemporaneity of the diastrophic movements, with which the paper deals, are based to considerable extent on the forementioned type of evidence. For example, included among the disturbances said to occur at the end of the Silurian, is one in Alaska which is based on the metamorphism of pre-Devonian rocks.[2] Again in the "Westphalo-Cardonides" deformations[3] reference is made to Haug[4] concerning certain ranges between central Siberia and South Asia. Here evidence shows only that Carboniferous formations are involved in the folding. Among the "Permo-Carbonides" deformations the folding of the Russian Geosyncline[5] is given. Concerning this Suess[6] shows that Permian strata are involved, but Jurassic is the first formation overlying the unconformity.

Since there appears to have been a general emergence of the lands at the close of the Paleozoic, it is only natural to expect that the last marine strata involved in any subsequent folding which occurred before the next marine invasion should be Carboniferous or Permian. Since any non-marine strata which may have been deposited in the meantime would probably be unfossiliferous, these would be likely to be neglected, although they might represent parts of the Triassic or later periods. Thus all post-Paleozoic and pre-Cretaceous deformations are likely to be called Permian.

Another point that must be remembered is that much of the evidence for the times of diastrophism is very inaccurate so far as

[1] *Op. cit.*, Vol. XXII, p. 315.

[2] R. T. Chamberlin, *op. cit.*, Vol. XXII, p. 326.

[3] *Ibid.*, p. 340.

[4] Emile Haug, *Traité de Géologie*, II (1911), 834.

[5] R. T. Chamberlin, *op. cit.*, Vol. XXII, p. 342.

[6] Ed. Suess, *The Face of the Earth*, Sollas Trans., Vol. I, p. 505.

the fossils are concerned because of wrong identifications and faulty interpretation of the restriction of certain species. For example, the Laramie, after which many of the Rocky Mountain deformations are supposed to have occurred, has proven to be a fictitious horizon so that it is difficult to say whether the different ranges were contemporaneous or not. The extermination of a fauna seems often to have been due to diastrophism. If diastrophism came at a somewhat different time in one part of the world than another, the faunas might change at correspondingly different times. This also might make diastrophism appear to have been contemporaneous, when it actually was not.

UNRECORDED DIASTROPHISM

Even if we consider that the evidence for diastrophism shows a greater amount of deformation at certain times during the geological history, there is good ground for doubting the validity of such evidence so far as it goes to prove that diastrophism was periodically intensified. In some parts of the geological column we find almost no traces of life, in others the remains of life are most abundant. The conclusion drawn from this evidence is not that life became almost extinct at times, but that conditions for its preservation were not as good. The same thing has probably been true of mountain building. The rapid oscillation of marine incursions have in some cases preserved the diastrophic record with more accuracy than when there were long intervals on either side of the diastrophism without marine invasions.

Various other ways in which diastrophism is likely to have occurred without leaving a record can be suggested. A few of these will be discussed.

1. *Records removed by erosion or deposition.*—If great erosion follows the development of a mountain range, it is always possible for the fossilferous beds which were involved in the folding to be removed and for pre-Cambrian metamorphics or intrusive cores to be the only remnant of a folded system. If erosion continues in the Colorado Rockies along the sides of the Front range, the upturned sedimentary rocks, which give evidence as to the time of the disturbance, may be removed leaving only a metamorphic core.

Such a range might be considered as pre-Cambrian. If deposition covers an old range, it may remain undiscovered until drill cores cut through the overlying sedimentaries. The buried granite ridges of the Mid-Continent oil fields are examples of such occurrences.

2. *Rejuvenation unrecorded.*—Most of the fairly recent mountain ranges show evidence of rejuvenation following their first uplifts. Such rejuvenation probably indicates a shortening of the earth's crust and should be considered in estimating the importance of diastrophic movements during the history of geology. It is only reasonable to suppose that the earlier ranges were also rejuvenated. Some of them are still ranges of considerable size and show undoubted rejuvenation. Usually the records of such renewed deformation are lacking. It is not unreasonable to suppose that such deformations may have helped make up for the deficiency of diastrophism during certain periods. For example, during the Cambrian where the diastrophic record is lacking, there may have been considerable deformation in the old pre-Cambrian ranges. It is even not improbable to suppose that what we consider to be pre-Cambrian folding is actually in some cases of early Paleozoic age with the disturbance involving only older sediments, either because of the local absence of the more recent sediments or because the Paleozoic present has been metamorphosed.

3. *Diastrophic records submerged.*—Since there is constant changing of the distribution of the lands, it is not unreasonable to suppose that the roots of old mountain ranges may be at present submerged beneath the sea. The old land of Appalachia is at least so buried in part. If this land supplied sediment to the Appalachian trough through much of the Paleozoic, it is likely that it was a mountainous country. The Carboniferous conglomerates of southeastern New England probably came from a land to the east of the present coast line. The thickness and coarseness of these conglomerates indicates without much question that they came from mountain ranges. Such sedimentary records have been neglected in considering the times of diastrophic movements, but they are reliable evidence of orogeny.

4. *Sub-oceanic diastrophism.*—A common fallacy among geologists is to consider that most of the orogenic diastrophism has

occurred on the continents and little of any importance on the sea bottom. Estimates of the amount of shrinkage of the globe are made by computing the amount of folding in the ranges on the lands and allowing nothing for crustal shortening beneath the seas. If the earth's interior is shrinking and the outside crust fitting itself to a smaller interior, unless the ocean bottoms show no evidence of past diastrophism, it would seem totally unreasonable to suppose that all of the shortening occurred within the lands which form such a small percentage of the total surface.

That diastrophism is going on today beneath the ocean basins is suggested by the numerous active volcanoes which occur within the confines of these basins. The location of the epi-centers of earthquakes shows more disturbance on the ocean bottoms than within the lands. To be sure, some of these earthquakes may be due to subsidence because of the weighting down of sediments derived from the lands, but much of the area disturbed is outside of the zone where continental sedimentation is occurring. On land we commonly consider vulcanism as the accompaniment of diastrophic movements. It is not altogether unreasonable to suppose that the same is true of the ocean basins.

It has been said in regard to submarine diastrophic movements that once these ranges were formed there would be nothing to put them out of existence since there is no erosion on the ocean bottom.[1] These ranges might then be thought to attain great heights and to produce great irregularities. Isostatic adjustment may have prevented the development of these ranges to very great elevations. They might go out of existence or be very much reduced in elevation either by the shifting of the zone of shortening with a resulting collapse, by the transference or cooling of a magma body beneath them, or in the other ways suggested in a previous article.[2]

Several things must be borne in mind in regard to sub-oceanic diastrophism. It would not be as concentrated as on the lands because there could be no geosynclines on the sea bottom, the irregularities produced by erosion would be missing. Diastrophism under

[1] T. C. Chamberlin, *Jour. of Geol.*, Vol. XXII, p. 315.

[2] F. P. Shepard, "Isostasy as a Result of Earth Shrinkage," *Jour. of Geol.*, Vol. XXXI, p. 212.

the oceans would produce broad plateau-like uplifts rather than closely folded mountain ranges. Are such plateau ranges absent on the sea bottom? Unfortunately soundings of the ocean basins are not very numerous so that there is a tendency to think of the ocean bottoms as being broad flat plains without important relief. However, if we compare sections made across the Atlantic with sections across the United States giving the same number of readings in each case, we find that the sub-oceanic surface has as great major variations in contour as has the land. Figure 1 represents such a

A

B

FIG. 1.—A comparison of sections with same vertical scale and similar horizontal scale giving the higher points of the Atlantic Ocean and the United States. *A*, Section of the bottom of the Atlantic Ocean. *B*, Section across the United States.

section. The data for the Atlantic ocean was obtained from soundings made by the Challenger Expedition.[1] Soundings taken recently by a United States destroyer show a more detailed section of the Atlantic,[2] which shows still greater irregularities (Fig. 2). Very likely there are great plains on the sea bottom, but these are probably only especially pronounced on the continental platform where recent deposition has evened up irregularities. Plains on the continents are more numerous than hilly surfaces. Such islands as the West and East Indies represent the higher mountain ranges of the ocean bottom.

If we can grant that there has been important diastrophism on the ocean bottom in the past, then it becomes much more difficult to prove that there has been periodic diastrophism. On the other

[1] Wyville Thompson, "Voyage of the Challenger," the *Atlantic*, Vol. I, p. 172.

[2] *Scientific American*, May, 1923, p. 330.

hand the idea of submarine diastrophism gives us a new method of strengthening the case for continuous diastrophism.

The periodic advance of epi-continental seas.—It is generally admitted among geologists that at certain times during geological history the continents were widely submerged. It is notable that such times were the occasions when diastrophic evidence is especially scarce. On the other hand, where the evidence for diastrophism is especially good, as at the end of the Paleozoic and in the late Tertiary, the continents were widely extended. There may be more significance to this occurrence than is commonly assumed.

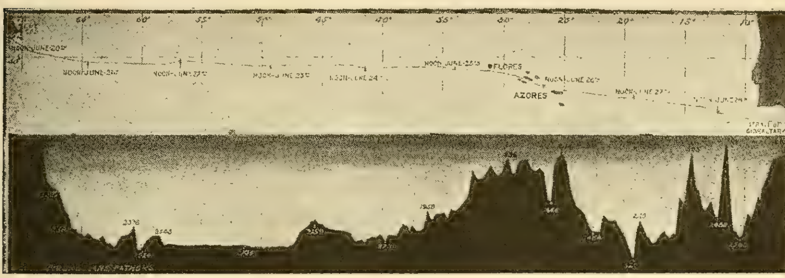

FIG. 2.—A cross-section of the ocean bottom. Vertical scale about 150 times the horizontal. (Courtesy of the *Scientific American.*)

T. C. Chamberlin explains these marine oscillations by a combination of two factors.[1] One of these is the periodic depression of the ocean basins which causes the draining of the lands and the other, the transporting of sediment out into the ocean, thus raising the sea-level, which causes submergence of the lands until there is a new depression of the sea bottom.

While the idea of the periodic depression of the ocean basins is quite commonly accepted, the basis for such an idea is difficult to discover. Presumably it is supposed that the lands are eroded and the ocean basins covered with sediment until they are so weighted that they sink under the burden. However, it must be remembered that the larger part of the oceanic basins is receiving almost no sediment, as is readily shown by the presence of Cretaceous fossils in the oceanic dredgings. Could this slow sedimentation be expected

[1] Chamberlin and Salisbury, *Geology* (1906), Vol. I, p. 57.

to cause the large variations in the sea-level in a relatively short period of time? If the evidence for the greater density of sub-oceanic material is correct, there is every reason to believe that the ocean basins owe their depth to this extra density. They should have become adjusted to this difference early in geological history, just as the earth has adjusted its oblateness to its rate of rotation. As there has been presumably little addition or subtraction from the basins, there is little reason to believe that they should have to renew this adjustment periodically. If the zones along shore sink, due to loading, the compressive effect of such shrinking would be negligible because of the narrowness of the zone.

As to the second point, let us see what the effect of erosion would be as to raising the sea-level. It must be remembered that sediments are not all carried to the ocean directly, but that there is a most important amount of deposition in the interior in river basins. Let us suppose there was a sea incursion up the Mississippi due to some slight raising of the sea-level. The Mississippi and its lower tributaries would begin to deposit in this sea and would build out the land much more rapidly than they would raise the sea-level by displacing the sea. Of course, if erosion continued long enough there would be a tendency to submerge parts of the lands, but for long periods after a great upheaval of the continents or a sinking of the sea-level the continental boundaries might be expected to be spread out rather than to retreat so far as erosion and deposition are concerned. The oscillations accompanying the advance and the retreat of the seas could hardly have been produced by the displacement of the water by sedimentation. Orogenic disturbances could easily have produced such an effect.

If diastrophism is periodic and world-wide in its effects, it is only reasonable to infer that during a disturbance there would be folding in parts of the ocean basins as well as in parts of the continents. If this were the case, the sea-level would rise and the lower parts of the continents, which were not affected by the diastrophic movements, would be submerged.

If on the other hand we consider that diastrophism has been continuous, but at some times more concentrated under the oceans and at others more concentrated within the continents, we can

explain at the same time the apparent periodicity of orogeny, if there is such, and the periodic incursions of the sea. When the ocean bottom was taking up the brunt of the shortening of the crust, the sea-level would rise in relation to the lands. Then when the chief orogenic disturbances were within the continents, the bottom of the sea would be relatively depressed and the epicontinental seas would be drained.

THEORETICAL CONSIDERATIONS

Is it not questionable whether the idea of periodic diastrophism would ever have originated had it not been for some early field evidence which suggested it? If the interior of the earth is shrinking constantly, whether at an increasing or a decreasing rate, the non-shrinking outer crust might naturally be expected to fit itself to the interior without interruption. The crust is variously computed to support from $\frac{1}{200}$ to $\frac{1}{500}$ of its own weight so that it is not reasonable to expect the rigidity of the crust to allow an open space to develop underneath due to the contraction of the interior without a wrinkling of the crust to fit it.

If the crust could store up stresses for a long period before giving away to them as suggested by Chamberlin,[1] would it not be reasonable to suppose that diastrophism would occur in only one zone after the breaking point was reached? Once one zone of weakness collapsed, the pressure on other points, where relief was apt to take place, would be reduced and a crowding toward the range where deformation had set in would be expected, while quiet prevailed elsewhere. This state of affairs is not what is looked for by the advocates of periodic diastrophism, but on the contrary they speak of a contemporaneous development of diastrophic movements in many parts of the world.

If the crust is rigid enough to store up stresses during long periods, then burdening of the crust would not be expected to cause yielding for long periods. The constant warping of the crust in many parts of the world during the present cycle suggests that the crust is rather easily disturbed from its state of equilibrium. This warping is especially significant if we agree with T. C. Chamberlin in believing that the present isostatic condition of the crust is due to

[1] T. C. Chamberlin, *Jour. of Geol.*, Vol. XXVII (1918), p. 193.

recent world-wide movements which have removed the long accumulated strains.[1] The great glaciers which came down over Canada and northern United States appear to have caused a decided depression of the land, which is shown by the great uplifts which have occurred since the ice retreated.[2] During the formation of geosynclines there must have been subsidence at about the same rate at which the sediment was added. This suggests that the burdening due to the addition of the sediment was important enough to have some effect on the deformation of the crust. Earthquakes are said to be very common in the submarine portions of deltas offering another indication of the weakness of the crust. Also if the crust is actually in an isostatic condition in all places, it must be very weak. Thus the plea for a crust strong enough to accumulate strains through long ages and then give away with great momentum is not supported by observations.

It would be foolish to deny that the earth is rigid to stresses of short duration, but when stresses are applied over fairly long periods of time, thousands of years for example, the most rigid of bodies may yield. Experiments on the strength of material may have sufficient pressure to be compared to the forces acting beneath miles of rock, but those experiments cannot be continued long enough to give any idea of the effect of the time factor.

Crustal creep toward mountain ranges.—A point which seems to have been neglected by most geologists who believe in the shrinking of the earth, is the means by which all of the shortening of the crust is concentrated within a relatively small portion of the earth's surface, namely the mountain ranges. If a balloon is inflated and covered with paraffin and some parts of this paraffin are thinner or weaker than other parts, allowing some of the air to escape from the interior of the balloon will cause crumpling to take place in the weaker zones of the paraffin while the remainder of the paraffin slides along the surface of the balloon toward these zones of crumpling.[3] The shrinkage of the earth with the resulting development of plains and mountain ranges must be a process very similar to this.

[1] T. C. Chamberlin, *Jour. of Geol.*, Vol. XXVII (1918), p. 197.

[2] R. A. Daly, *Bull. Geol. Soc. America*, Vol. XXXI (1920), p. 303.

[3] R. T. Chamberlin and F. P. Shepard, "Some Experiments in Folding," *Jour. of Geol.*, Vol. XXXI (1923), pp. 495–96.

If after some deformation a mountain zone becomes strong enough to resist further deformation, the parts of the crust which were sliding toward it, will start moving toward another zone of greater weakness, while deformation in the first zone may cease for a long period of time. Is it not just this change of the location of the site of deformation, rather than the cessation of movement, which has lead many to believe in the hypothesis of periodic diastrophism?

SUMMARY

Periodic diastrophism is taken to mean world-wide periodicity of orogenic movements and not local periodicity. This hypothesis appears to have three fundamental weaknesses. First, geological evidence shows a series of diastrophic movements which are almost continuous from the Ordovician to the present. Second, the belief in an excess of diastrophism at some epochs of geological time over those of other epochs is due either to the common assumption that diastrophic movements come at the end of a period, when the evidence is not sufficient to justify such conclusions; to the records of diastrophic movements having been erased at some times more than at others; to the unrecorded evidence of sub-oceanic diastrophism which probably alternates in intensity with continental diastrophism as is shown by the record of epi-continental seas; or to the shortening of the crust by minor flexures which leave no record of their time, but probably are important in amounts. Thirdly, theoretical considerations show that the idea of periodic diastrophism is contrary to what would be expected of a shrinking globe, which as geological evidence suggests has a crust that is rather easily disturbed by differences of weighting and therefore could not be expected to accumulate large strains. Further, the crust would have to support a large part of its own weight in order not to fit itself constantly to a shrinking interior and it is believed that it can support only a small fraction of its own weight.

Although admitting the possibility that future accurate studies may demonstrate that diastrophism has been periodic, it seems clear to the writer that in view of our present knowledge of the subject each of the three weaknesses cited form a serious barrier in the way of the acceptance of the hypothesis and taking them altogether there is little reason to believe in periodic diastrophism.

REVIEWS

Geology and Ore Deposits of the Yanahara Mining District, Province of Mimasaka, Japan. By TAKEO KATO. Japanese Journal of Geology and Geography, Transactions and Abstracts, Vol. I, Nos. 3–4, Tokyo, 1922, pp. 77–116, plates XIII–XVIII and text-figures 1–13.

These numbers of Volume I are devoted principally to a report in English by Professor Takeo Kato, of the University of Tokyo, on the geology and ore deposits of the Yanahara mining district, formerly a producer of oxidized iron ores, now an important producer of high-grade pyritic ores. The deposits are shown to be replacement deposits in metamorphosed rocks, both igneous and sedimentary. The presence of pyrrhotite, tourmaline and actinolite indicate high temperature conditions of formation. The mineralizing solutions, it is clear, came from the batholitic intrusions of granitic rocks common in the region.

On pages 31 to 48 a number of abstracts in English are given of geologic papers published in Japan.

E. S. B.

Bulletin of the Geological Society of China, Volume I, 1922, and Volume II, 1923. Published by the Society, Peking, China.

There has come to the Editor's desk Volumes I and II of the *Bulletin of the Geological Society of China*, published at Peking. The Geological Society of China was organized in the Library of the Geological Survey in Peking in January, 1922, with twenty-six charter members. The president of the new society is Dr. H. T. Chang, chief of the Division of Geology of the Geological Survey.

The Bulletin, published in English, is the official organ of the Society and will contain proceedings of the meetings and papers presented at the meetings either in full or in abstract. Its editor is Dr. V. K. Ting, director of the Geological Survey.

Among the longer articles in Volumes I and II dealing with problems of Chinese Geology are: "The Sinian System," by Amadeus W. Grabau, professor of petrology in the National University of Peking; "The

Tsinan Intrusive," by George B. Barbour; "The Constitution of Coal," by Chung Yu Wang, in addition to numerous shorter papers and abstracts.

E. S. B.

Revision of the Flora of the Green River Formation with Descriptions of New Species. By F. H. Knowlton. United States Geological Survey, Washington, *Professional Paper 131-F*, 1923. Pp. 133–76, pls. 36–40.

The Green River formation, formerly known as the Green River shales, was named and described by F. V. Hayden in 1869. He recognized it as being of purely fresh-water origin, and of middle Tertiary age. Hayden showed full appreciation of its flora and fauna, and he understood the great economic value of these shales for their oil contents.

After dropping a number of names which had been formerly adopted for the Green River flora by Lesquereux and others, Knowlton accepts a list of plants among which the following groups are represented. There are five well-marked fern types. No remains of conifers have been reported, with the exception of some pollen grains. The monocotyledons are better represented, and the best of all are the palms, of which there are three nominal forms referred to different genera. Among the dicotyledons are represented:

Salix	*Ailanthus*
Myrica	*Rhus*
Juglans	*Sapindus*
Quercus	*Ilex*
Ficus	*Rhamnus*
Brasenia	

Knowlton's inferences point toward a lowland flora which required a climate that was at least warm, and possibly bordered on subtropical. He also distinguishes an upland flora requiring unquestionably warm and temperate climatic conditions. These deductions from the floral elements are supported by the insect fauna of the Green River formation. This fauna comprises a certain element that indicates tropical surroundings, and another that indicates cool, or perhaps temperate, conditions.

A. C. N.

The Geology and Mineral Resources of the Collingwood Subdivision, Karamea Division. By M. ONGLEY and E. O. MACPHERSON. New Zealand Department of Mines, Geological Survey Branch, Bull. 25 (N.S.). Wellington, 1923.

Ammergauer Studien: I. Die Pflanzendecke in ihren Beziehungen zu den Formen des alpinen Hochgebirges. Von DR. L. LOEGEL. *II. Kare und karähnliche Formen in den Ammergauer Bergen.* Von STUDIENRAT W. STADELMANN. Mit 9 Tafeln. Ostalpine Formenstudien, Abteilung 1, Heft 5. Berlin: Gebrüder Borntraeger, 1923.

Vor Verdun. Von DR. FR. STURM. Die Kriegsschauplätze, 1914–1918, Geologisch dargestellt, Heft 4. Berlin: Gebrüder Borntraeger, 1923.

Guide to the Collection of Gemstones in the Museum of Practical Geology. By W. F. P. MCLINTOCK. 2d ed. London: Printed under the Authority of His Majesty's Stationery Office, 1923. Price 1*s.* 0*d.*, net.

Problems of the Great Barrier Reef. By H. C. RICHARDS. Queensland Geographical Journal, Vols. XXXVI–XXXVII.

Anorthoclase Basalt from Mapleton, Blackall Range, South-Eastern Queensland. Proc. Royal Soc. of Queensland, Vol. XXXIV, No. 6. Brisbane, 1922.

An Unusual Rhyolite from the Blackall Range, South-Eastern Queensland. By H. C. RICHARDS. Proc. Royal Soc. of Queensland, Vol. XXXIV, No. 11. Brisbane, 1922.

Essays on the Cenozoic of Northern China. By J. G. ANDERSSON. Memoirs of the Geological Survey of China. Series A, No. 3, March, 1923. Peking.

Bulletin of the Geological Survey of China, No. 4, October, 1922. Peking.

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Among articles to appear in early numbers of the *Journal of Geology* are the following:

The Structural Relations of the Bushveld Igneous Complex of the Transvaal. By G. A. F. MOLENGRAAFF and R. A. DALY.

The Contrast in the Effect of Granite and Gabbro Intrusions on the Ely Greenstone. By G. M. SCHWARTZ.

Post-Pleistocene Volcanics of the British Columbia Coast. By V. DOLMAGE.

The Verden Sandstone. By R. D. REED and NORMAN MELAND.

General Features of Pre-Cambrian Structure along the Big Thompson River in Colorado. By MARGARET BRADLEY FULLER.

The Correlation of the Lower Allegheny-Pottsville Section in Western Pennsylvania. By B. COLEMAN RENICK.

Footprints in Pennsylvanian Sandstones of Colorado. By JUNIUS HENDERSON.

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THE

JOURNAL OF GEOLOGY

November-December 1923

THE CHANNELED SCABLANDS OF THE COLUMBIA PLATEAU

J HARLEN BRETZ
University of Chicago

OUTLINE

DEFINITION OF "SCABLAND"

The terms "scabland" and "scabrock" are used in the Pacific Northwest to describe areas where denudation has removed or prevented the accumulation of a mantle of soil, and the underlying rock is exposed or covered largely with its own coarse, angular débris. The largest areas of scabland are on the Columbia Plateau in Wash-

ington, north of Snake River. These scablands have a history which is believed to be unique. The prevailing feature of their topography is indicated in the term here used: channeled scablands.[1] They are scored by thousands of channels eroded in the underlying rock. The plateau in Washington, north of Snake River, has a total area of about 12,750 square miles, of which at least 2,000 square miles is channeled scabland. The scabland is widely distributed over the region in linear tracts among maturely dissected hills which bear the loessial soil (wheat lands) of the plateau.

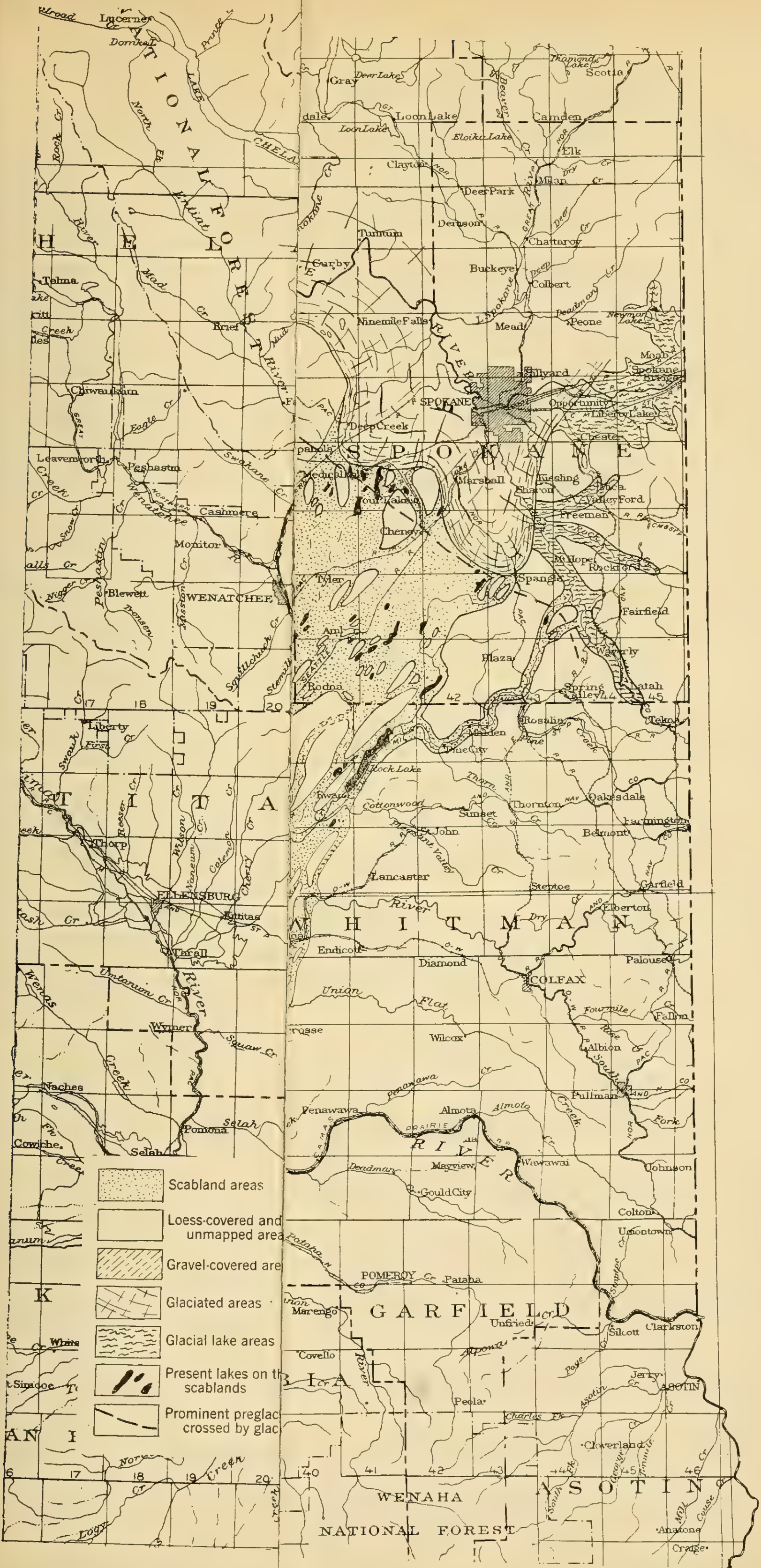
PHYSIOGRAPHIC RELATIONS OF THE CHANNELED SCABLANDS

The following features and relations of the scablands exist in all tracts. They must form the basis of any interpretation for the origin of channeled scabland. The map should be examined as this list is read.

1. Scabland tracts are developed invariably on or in the Columbia basalt formation.
2. Scabland tracts are invariably lower than the immediately adjacent soil-covered areas.
3. Scabland tracts are invariably elongate.
4. The elongation of scabland tracts is with the dip slope of the underlying basalt flows. There are eight known exceptions to this rule,[2] all minor affairs so far as length is concerned.
5. Scabland tracts, considered as units, invariably have continuous gradients.
6. Scabland tracts are invariably bounded by maturely eroded topography.

[1] An earlier paper on this subject was published by the writer in the *Bulletin of the Geological Society of America*, Vol. XXXIV (1923), pp. 573–608. The study on which it was based involved about a 1,000-mile traverse of the plateau. Since then, the writer has studied the plateau more thoroughly, having added more than 2,000 miles to the previous total traverse. Much more detailed information and several modifications of the earlier interpretations justify the appearance of a second paper on the subject. The accompanying map (Plate III) is based on a field examination of every scabland there indicated. In a few places the boundaries are inferred (dashed lines) but future work will hardly do more than make minor changes or additions.

[2] A part of Othello Channels, a part of Drumheller Channels, at Palisades and near Spencer in Moses Coulee, at Soap Lake and near Bacon in Grand Coulee, 6 miles south of Almira on Wilson Creek, and at Long Lake in Spring Coulee.


Scabland areas
Loess-covered and unmapped area
Gravel-covered are
Glaciated areas
Glacial lake areas
Present lakes on the scablands
Prominent preglac crossed by glac
SPOKANE
WHITMAN
GARFIELD
ASOTIN
WENATCHEE
ELLENSBURG
COLFAX
POMEROY
WENAHA NATIONAL FOREST
Cheney
Spangle
Rosalia
Rock Lake
Pullman
Clarkston

THE CHANNELED SCABLANDS OF THE COLUMBIA PLATEAU AND THEIR ASSOCIATED FEATURES

The small squares are townships and indicate the scale of the map

7. Scabland tracts are developed in pre-existing drainage lines of the mature topography.[1]

8. Scabland tracts are connected with each other.[2]

9. (*a*) The areas surrounded by scabland invariably have the dendritic drainage pattern, mature topography and loessial soil of the plateau. (*b*) They are almost invariably elongate with the scabland tracts. (*c*) They commonly have steep marginal slopes descending from 50 to 200 feet to the scabland. These slopes are almost invariably in loess. Slopes of 30° to 33° are not uncommon. They are much younger topographically than the slopes of the valleys among these mature hills.

10. Scabland tracts with steep gradient are narrow, while those with gentle gradient are wide.

11. The pattern of scabland tracts, where hills of the older topography are isolated in them, is anastomosing or "braided."

12. Scabland tracts invariably contain "channels." These are gorges or canyons or elongated basins eroded in the basalt. The channels are invariably elongate in parallelism with the tract as a whole and, in most cases, the channel pattern is anastomosing or braided.

13. (*a*) Scabland tracts invariably bear discontinuous deposits of basaltic stream gravel. (*b*) These deposits invariably contain a small proportion of pebbles and cobbles of rock foreign to the plateau. (*c*) These deposits invariably rest on an eroded, scabland surface of the basalt. (*d*) They commonly lie on the down-gradient side of eminences in the scabland.

14. (*a*) Scabland tracts invariably bear scattered bowlders of foreign rock. (*b*) The proportion of foreign débris, either the fragments in the gravel or the scattered bowlders, is invariably smaller with increasing distance down-gradient.

15. Scabland tracts are invariably without a mantle of residual soil.

16. Scabland tracts are traceable up-gradient to a narrow basalt plain bordering the south side of Spokane River in the northern

[1] There are many exceptions to this rule, occurring where scabland tracts cross pre-existing divides, but the total length of such is only a small fraction of the aggregate length of all scabland tracts.

[2] Moses Coulee is the only exception.

part of the plateau.[1] This basalt plain bears many glaciated erratic bowlders and some patches of till, but no channeled scabland, no mature topography, and no loessial soil.

17. Only where the minor valleys of the mature topography adjacent to this basalt plain open northward on to the plain are any glacial erratics found in them.[2]

18. There are but ten scabland openings to this basalt plain to the north.

19. Scabland tracts are invariably traceable down-gradient to Snake River on the south or to Columbia River on the west. There are nine places where scabland tracts enter these two streams Only three of them were drainage ways before the scablands were formed.

20. There is no channeled scabland on the plateau in western Idaho or south of Snake River or west of Columbia River.

21. Nowhere in the scablands or the maturely dissected country, during ten weeks of field study, has a till been found, or any deposit of doubtful genesis which could be interpreted more satisfactorily as till than as non-glacial in origin.[3]

GENERALIZED STATEMENT OF THE ORIGIN OF THE CHANNELED SCABLANDS

This unique combination of topographic features of the Columbia Plateau in Washington has only one interpretation consistent with all the foregoing items. The channeled scablands are the erosive record of large, high-gradient, glacier-born streams. The basalt plain records the southern limit reached by the ice sheet from which these streams took origin. Before this glaciation occurred, the entire plateau of Washington was covered with a loessial soil, varying in depth from a few feet to 200 feet. This and the underlying basalt had been eroded to maturity and a network of drainage lines covered it. The major water courses of this mature topography were consequent on the warped surface of the

[1] Grand Coulee and Moses Coulee are exceptions. Grand Coulee opens up-gradient into Columbia River Valley and the upper end of Moses Coulee is obliterated by the drift of a later glaciation.

[2] Exceptions due to a later episode in the history of the region are noted later.

[3] One exception, noted later.

plateau which descends in a general way from the northeast to the southwest.

The ice sheet approached and invaded the plateau from its northern high margin. It barely crossed to the headwaters of the consequent drainage. In places, it did not cross, but by blocking all other escapeways, its waters were forced to cross. By about a dozen different routes, at different altitudes and distributed along more than 150 miles of the ice front, water entered the mature drainage system. The capacity of the pre-existing valleys was wholly inadequate for the volume of most of these streams. Furthermore, gradients were high and the glacial waters eroded enormously, sweeping away the overlying loessial material, crossing low divides and isolating many groups of the maturely eroded hills to produce the anastomosing pattern of the scablands, biting deeply into the basalt to make the canyons and rock basins, and spilling into the Snake and Columbia in three times as many places as the pre-existing drainage had used.

This procedure of glacial streams was unique, so far as the writer is aware. It was unorthodox, at any rate, for no valley trains and but two outwash plains[1] were built on the plateau south of the basalt plain. The stream gravel of the scablands is almost wholly in separate bars.

The conception above outlined is amply sustained by every feature and relationship of the scablands. All other hypotheses meet fatal objections. Yet the reader of the following more detailed descriptions, if now accepting the writer's interpretation, is likely to pause repeatedly and question that interpretation. The magnitude of the erosive changes wrought by these glacial streams is nothing short of amazing. The writer confesses that during ten weeks' study of the region, each newly examined scabland tract reawakened a feeling of amazement that such huge streams could take origin from such small marginal tracts of an ice sheet, or that such an enormous amount of erosion, despite high gradients, could have resulted in the very brief time these streams existed. Not River Warren, nor the Chicago outlet, nor the Mohawk channel,

[1] The Hartline gravel flat and the Quincy basin fill, both in structural depressions in the plateau.

nor even Niagara falls and gorge itself approach the proportions of some of these scabland tracts and their canyons. From one of these canyons alone[1] 10 cubic miles of basalt was eroded by its glacial stream.

THE BASALT PLAIN, NORTH OF THE SCABLANDS AND MATURE TOPOGRAPHY

This physiographic feature extends westward from Spangle for 50 miles along the south side of Spokane River and varies from 3 to 12 miles in width. It is determined by the upper surface of the Columbia basalt formation. It is interrupted in places by short valleys tributary to Spokane River, and the different portions are known as prairies.[2] This plain is bounded on the south by channeled scabland and maturely eroded loessial hills. The differences between it and adjacent broader scablands are not marked, but the loessial hills are in striking contrast with it. These hills which, elsewhere on the plateau, come right to the edge of Snake and Columbia valleys,[3] nowhere overlook the Spokane Valley. They terminate abruptly on the southern margin of this plain. On the plain there is no mature topography and no channeled scabland. There is no area on the plateau like it. The nearest approach to it is the northern portion of Douglas County, back of the Wisconsin terminal moraine. This narrow plain must be the result of conditions which prevailed no farther south.

These conditions can be summed up in one word—glaciation. Deposits of till and many striated erratics have been found in every township examined on it. The till is patchy in distribution. No moraine margins the southern edge of the plain and no good moraine ridges occur on it, though here and there is morainic topography.

The genesis of the plain thus established, the questions of its character before glaciation and the method of its development arise. These are answered clearly when the adjoining mature loessial topography is studied. The larger valleys of this topog-

[1] Upper Grand Coulee.

[2] Paradise Prairie, Sunset Prairie, Indian Prairie, Four Mound Prairie, etc. On the north side of Spokane River are Pleasant Prairie and Five Mile Prairie, also parts of this plain.

[3] With the exception of northern Douglas County.

raphy have been eroded to varying depths into the basalt. The bottoms of such as lead out across the basalt plain to the north are lower among the hills than the general surface of the plain. The profile of the plain, extended back among the hills, cuts their slopes somewhere between hill summits and valley bottoms. And this transection is at the contact of loess on basalt. The ice sheet which covered the plain, therefore, simply removed the upper, weaker formation, and only to a minor extent altered the surface of the basalt formation.

THE MATURE TOPOGRAPHY

This is the dominant type of topography of the Columbia Plateau. The major drainage lines are structurally controlled, but the minor ones constitute a dendritic network. The pattern is eroded largely in a weak sedimentary deposit, chiefly loessial, which overlies the basalt. Maturity is expressed in the complete development of the drainage system, in the reduction of the original surface to valley slopes[1] and in the concavity of the lower part of many of these slopes. This maturity has been developed with reference to the underlying basalt as a base level, for progress of the cycle of erosion in the loess has been very much more rapid. Neglecting the loessial cover, the basalt plateau is in early youth, and will still be when the loess has been entirely removed. Nevertheless, the absence of deep trenches in basalt in the interior of the plateau, similar to Spokane, Columbia, and Snake River valleys about its margin, and the cutting through of the loess has allowed the development of shallow mature valleys in the upper part of the basalt.

The loessial deposit varies in thickness, in some places being only a soil, and in others being 200 feet or more in thickness. It is not all loess. There are places where it is chiefly a residual soil from the basalt, and others where it is a waterlaid sediment.[2] But many widely distributed sections show a succession of loessial deposits,

[1] A few broad, undissected divides are still left. Michigan Prairie, south of Lind, is a good example.

[2] Probably the Ellensburg formation. The Pleistocene Ringold formation, in Franklin County, is younger than the mature topography.

with abundant root and rootlet casts throughout and with reddened upper surfaces of each deposit, aggregating 50 feet or more.[1]

The mature topography is older than the scablands and the basalt plain. Literally hundreds of isolated groups of maturely eroded hills of loess stand in the scablands. Their gentle interior slopes are identical with those far from the scabland tracts. But their marginal slopes, descending to the scablands, commonly are very steep, over large areas amounting to 30° and even 35° (Figs. 1, 2, and 3). These steep slopes are seldom even gullied, except

FIG. 1.—One of a group of loessial hills in the scablands a few miles southwest of Rock Lake. One of the steepened slopes and its alignment are shown. Photo by O. C. Clifford.

where a drainage line leads out from the hill group to the scabland. Where the minor valleys transected by the steep slopes lead backward into the interior of a hill group they are simply hanging valleys.

There are few places where basalt occurs in these steepened slopes. Where present, it is always restricted to the lower part and shows itself in conspicuous ledges.

A very striking and significant feature of the steepened slopes is their convergence at the northern ends of the groups to form great

[1] Near Harrington and near Kahlotus are two excellent cuts which show this very well.

prows, pointing up the scabland's gradient (Figs. 2 and 3). The nose of a prow may extend as a sharp ridge from the scabland to the very summit of the hill. It is impossible to study these prow-

FIG. 2.—An isolated loessial hill on the scabland south of Hooper. The prow of the hill is pointed at the observer. The hill is 180 feet high, more than half a mile long, has a very narrow crest, and sides which slope 35°. It is entirely surrounded by scrubbed basalt. Half a mile to the west is a canyon in the scabland 75 feet deep, with an abandoned waterfall at the head.

FIG. 3.—The same hill as shown in Figure 2. The prow is at the right. The corresponding steepened slope at the tail of the hill shows at the extreme left. Most of the apparent left slope of the crest is a matter of perspective. Photo by O. C. Clifford.

pointed loessial hills, surrounded by the scarred and channeled basalt scablands, without seeing in them the result of a powerful eroding agent which attacked them about their bases and most effectively from the scabland's up-gradient direction.

DETAILS OF A SCABLAND SURFACE

All scablands are channeled to a greater or lesser extent. These channels are eroded in basalt to depths varying from a few feet to

FIG. 4.—Devils Canyon at mid-length, looking south. A double fall existed here when the canyon was eroded. The island and the eastern part still remain.

hundreds of feet. Commonly there are many shallow channels on each tract. Most tracts also have a few deeper channels, of the proportions of canyons[1] (Figs. 4 and 5). All channels in a tract are intricately interlaced, resulting in a multitude of butte-like hills, knobs, and ridges among them. Few channels have

[1] Upper Grand Coulee (1,000 feet deep), Lower Moses Coulee (900 feet deep), Devils Canyon, Franklin County (500 feet deep), and Palouse Canyon (500 feet deep) are the most noteworthy examples.

accordant grades where they unite or diverge, the bottoms of the shallower ones hanging above the floors of the deeper ones. Many canyoned channels have abandoned cataracts and cascades in them or at their heads.[1] Most canyoned channels have elongated rock basins (see Fig. 6). Even in the shallow channels, basins or pockets in the rock are common. Some of these rock basins clearly were produced by recession of a cataract whose scarp still

FIG. 5.—Devils Canyon near mid-length, looking north. Note the scrubbed basalt ledges above the canyon rim, and the profile of the loessial bluffs, still higher and farther back.

exists.[2] Others were produced by plucking of the columnar basalt in the canyon floors where the gradient was high.[3]

These features of the channeled scablands on the Columbia basalt plateau do not closely resemble any other type of topography.

[1] Dry Falls (400 feet high) in Grand Coulee, The Potholes (350 feet high) south of Trinidad, Frenchman Springs (400 feet high) south of The Potholes, and The Three Devils (600 feet total descent) in Moses Coulee are especially noteworthy.

[2] Deep Lake, below one of the Grand Coulee abandoned falls, has many associated huge potholes, drilled into the basalt at the foot of the falls as they retreated. Each of the two cataracts of "The Potholes," south of Trinidad, has a single elongated rock basin at the foot (Fig. 7).

[3] Rock Lake in Whitman County, Goose Lake in Grant County, Washtucna Lake and Eagle Lake in Franklin County, Pacific Lake and Tule Lake in Lincoln County, Goose Lake in Grant County, Medical Lake, Silver Lake, and Farrington (Fish) Lake in Spokane County, and Big Swamp Lake and Cow Lake in Adams County are examples of hundreds of such basins.

The narrowness and elongation of channels and the continuous gradients of tracts as a whole suggest river valleys but these features are all inherited from pre-existing valleys. Furthermore, some tracts are nearly as broad as they are long. The pattern of channels on a tract, like the pattern of some tracts and their isolated loessial hills, is much like that of great braided streams (Fig. 8).

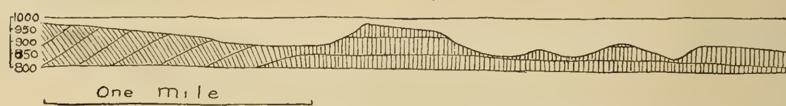


FIG. 6.—Longitudinal profile of the deepest of the Drumheller Channels across the nose of the anticline. Four rock basins are indicated, the largest of which is 75 feet deep.

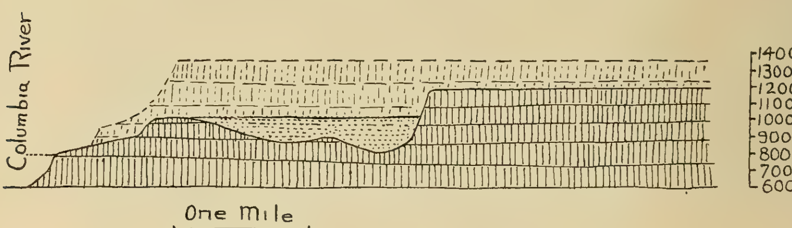


FIG. 7.—"The Potholes," longitudinal profile of the northern half, showing (1) cliff along northern side of the canyon, (2) amount of recession of the falls, (3) elongated rock basin below the falls, (4) great gravel bar along edge of the rock basin, and (5) approximate level of Columbia River when the cataract was formed.

But the scablands are erosional in origin, while the braided stream pattern is depositional.

The evidence for the origin of channeled scabland by stream erosion is overwhelming. The evidence of contemporaneity of action of all channels of a given tract, at least in its early history, is equally convincing. The only sequence indicated is that of development of the greater channels later in the epoch and consequent draining off of the shallower channels.[1] The scablands of the plateau in Washington are the beds of huge river courses in which

[1] Especially well shown in Lower Grand Coulee, in Moses Coulee between Palisades and Spencer, in The Potholes and Frenchman Springs south of Trinidad, and in Palouse Canyon south of Hooper, in all of which cataract recession in main channels cut off smaller channels alongside in the same scabland tract.

the streams once spread completely from side to side and only later became concentrated in the deeper canyons.

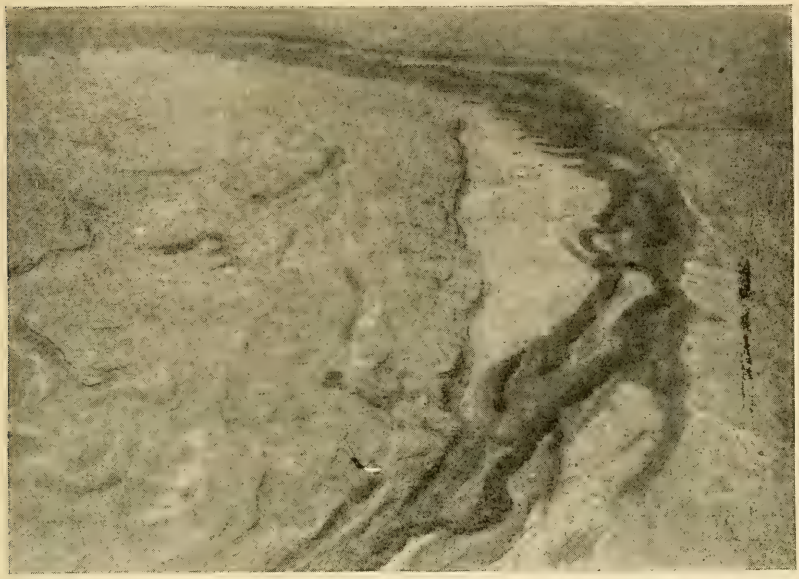


FIG. 8.—A part of Rock Creek (Lincoln County) and its associated scabland. The creek in the main channel is margined by vegetation. The scabland to the left is barren and the irregularity in lighting is due almost entirely to the cliffs which border the shallow anastomosing channels. (Aeroplane Photo by F. H. Frost.)

ALTITUDES AND GRADIENTS OF THE SCABLAND TRACTS

The heads of scabland tracts which are open to the basalt plain range in altitude between 2,350 and 2,500 feet above tide. There are six or eight of these, the number depending on just what is considered to constitute an individual scabland tract. At least the following should be recognized as unit tracts. The order in the list is from east to west.

1. Pine Creek channel. Altitude of head, 2,450 feet A.T.
   Gradient approximately 25 feet per mile
2. Cheney-Hooper tract
   Four heads:
   - *a*) Marshall-Spangle, altitude, 2350±
   - *b*) Four Lakes, altitude, ?
   - *c*) Medical Lake, altitude, 2,425
   - *d*) Deep Creek, altitude, 2,350±

   Total width of the group is 22 miles

Gradients:
  Spangle to Hooper, 21.9 feet per mile
  Cheney to Hooper, 22.6 feet per mile
  Medical Lake to Sprague, 24 feet per mile
  Medical Lake to Hooper, 22.5 feet per mile

3. Reardan channel. Altitude of head, 2,500+
   Gradient, Reardan to Odessa, 20 feet per mile
4. Davenport-Harrington channel. Altitude of head, 2,450±
   Gradient:
     Davenport to Harrington, 27 feet per mile
     Harrington to Odessa, 26 feet per mile
5. Telford tract
   a) Eastern head. Altitude, 2,500±
      Gradient:
        Rocklyn to Odessa, 30 feet per mile
        Rocklyn to Krupp (Marlin), 26 feet per mile
   b) Western head. Altitude, 2,500±
      Gradient:
        Near Creston to Krupp (Marlin), 32 feet per mile
        Near Creston to Wilson Creek, 30 feet per mile
      Total width of heads is 17 miles
   c) Wilbur branch
      Gradient:
        Creston to Wilson Creek, 32 feet per mile
        Wilbur to Wilson Creek, 25 feet per mile
        Almira to Wilson Creek, 26 feet per mile

The only scabland tracts which do not open on the basalt plain are Grand Coulee and Moses Coulee. For the head of Moses Coulee there are no altitude measurements. Grand Coulee has had a peculiar history, not yet fully deciphered, but the significant altitude at its head for present purposes is not the coulee floor (1,530 feet A.T.) but the scabland margining the brink of the canyon, about 2,500 feet A.T. The canyon has been cut subsequent to the first spilling over of glacial waters. The floor near Coulee City is 1,510 feet A.T. Most of this descent occurred within a few miles of Coulee City, the original slope being as steep as 20° in part and averaging perhaps 10° for 1,000 feet of descent. This is the chief reason for the great canyon across the divide. No other scabland head has been notably canyoned. None other had a gradient to exceed about 30 feet to the mile. All the canyons of the channeled

scablands are located in places of exceptionally steep original gradients.

If the channeled scablands are the product of stream erosion, and if all tracts are of the same age, the fact that the scabland heads vary in altitude, though all but two are open to the same glaciated basalt plain, can have but one satisfactory explanation. Each glacial stream must have had a source of water which was unconnected with the others. This means that the ice sheet whose melting yielded these streams must have covered the basalt plain and in most places must have been in contact with the mature loessial hills which separate the scabland heads. It means, furthermore, that but a few miles of ice front supplied the water for streams so huge that they flooded over many preglacial divides of the mature topography even in the southern part of the plateau. It was this flooding across divides which produced the scabland plexus of the plateau.

About 40 miles of ice front in one case[1] yielded water sufficient to denude a non-elongated tract 250 square miles in area of a loessial cover about 100 feet in maximum thickness. This was done by lateral planation in the preglacial drainage lines of the tract. These lines were so shallowly intrenched in the basalt and the volume of the water was so great that, as the loessial hills were eroded away, the flood spread over the entire area, 13 miles wide. Gradients were low, however, and it did not develop canyoned channels. Steeper gradients farther from the edge of the ice, and greater capacity of the preglacial valleys, held the waters within the confines of these valleys, but six such[2] were necessary to contain the flood and they were all greatly eroded in the underlying basalt.

Another large scabland area[3] is 75 miles long and 15 miles in average width. Its total descent is 1,850 feet. Its altitude at the head is the lowest of all such tracts. It differs from the one above in its notable linear extent, in the possession of a large number of isolated groups of loessial hills of the older topography, in its greater

[1] The Telford scabland and its dependencies.

[2] Coal Creek, Duck Creek, Lake Creek, an unnamed creek, Connawai Creek and Wilson Creek.

[3] The Cheney-Hooper area, extending from Spangle and Cheney to Snake River, south of Hooper.

gradient and in the development of canyons.[1] Though a much greater volume of water passed through this tract, the gradients were steep enough to draw off the flood and prevent a complete spreading over the area. Much water came to it from the ice margin to the east in Idaho and no estimate can now be made of the length of ice front which contributed to it. There were five or six places of distributary discharge where this flood crossed preglacial divides and one of them[2] eventually obtained most of the discharge. Along this distributary route, the glacial flood swept away the loessial hills for a width of 10 to 15 miles and eroded 500 feet into the basalt.

The glacial drainage route which possessed the highest crossing of the preglacial surface of the plateau is Grand Coulee. It also found the steepest gradient[3] and its volume was sufficient with this gradient to cause the deepest erosion in the basalt. Upper Grand Coulee, across the preglacial divide, is 1,000 feet deep. But its floor, after the epoch had closed, was lower than that of any other glacial drainage route at the head. In its early history it drew water from about 40 miles of ice front, but never spread widely. The gradient, determined here by exceptional warping of the basalt, prevented that. There was no noteworthy preglacial stream along its course. Grand Coulee is, therefore, the simplest but grandest case of canyon-cutting by glacial streams on the plateau.

DEPTH OF GLACIAL STREAM EROSION IN THE SCABLANDS

Criteria.—The courses of the larger valleys in the mature drainage system were determined by the warped surface of the basalt. The dominant feature of this warping is the southwestward dip from Spokane River and Columbia River on the north to Snake River on the south and Columbia River on the west. Many minor folds are superposed on this dip slope, so recent geologically that anticlines determine divides and synclines contain stream valleys.[4] Commonly, only the major valleys are intrenched in the

[1] Cow Creek, Rock Lake, and Creek and lower Palouse River now occupy the most striking of these canyons.

[2] Palouse River Canyon below Hooper.

[3] In one place, 1,000 feet in about a mile.

[4] Examples are Moses Coulee east of Palisades, Wilson Creek above Almira, Crab Creek below Corfu, Washtucna Coulee, Lind Coulee below Lind, Snake River near Lewiston and Clarkston, Union Flat Creek, Rebel Flat Creek, and Palouse River above Winona.

basalt. The minor valleys, in general, are not eroded through the loessial mantle.

Except near the bounding canyons of Spokane, Columbia, and Snake Rivers, or in exceptionally upwarped parts of the plateau, the preglacial valleys in basalt which were unviolated by the glacial flood, have the same mature slopes as those in the loess. Where glacial streams found routes eroded but slightly in basalt, they commonly spread widely at first[1] and only later eroded canyons, if they did so at all. Such wide scablands commonly are bounded by steep bluffs of loess. Many of the mature valleys in basalt were sufficiently capacious to contain the glacial waters which entered them. In such cases[2] the scabland of the route lies on the sides and bottoms only, and unsteepened slopes of the bounding older topography may come to the edge of the scabland. Such a tract is narrow and instead of having a multitude of lateral shallow channels anastomosing with the main canyon, it consists of exceedingly roughened ledges of basalt outcropping on the slopes of the main valley. Shoulders in the curves of these valleys were treated with especial vigor, in some cases being wholly cut away to leave prominent cliffs on the valley walls.

By smoothing out these ledges, something of the cross-section of the preglacial valley may be obtained. Remnants of the old floors are recorded in isolated buttes of basalt on the present floor and in the lowest prominent rock terraces, below which is the canyoned channel eroded in mid-current by the huge glacial stream.

Instances.—In Cow Creek, southwest of Ralston, the remarkable number of knobs and buttes in the lower part of the valley indicates clearly that the preglacial floor must have been at least 75 feet higher than the present. In Crab Creek Valley, between Krupp (Marlin) and Stratford, there are prominent buttes, isolated or partially isolated on the floor of the canyon. The tops of these are remnants of the preglacial floor and their height (100 feet in places) is a minimal measure of the depth of canyon-cutting by the glacial waters.

[1] As in the Telford and the Cheney-Hooper areas.

[2] Washtucna Coulee, Esquatzel Coulee, Lower Moses Coulee, Lind Coulee, Pine Creek above Rock Lake, Rock Creek (Lincoln County) and Coal Creek are examples.

In Washtucna Coulee, numerous prominent rock terraces from 150 to 200 feet above the present floor are probably remnants of the earlier valley bottom. In Esquatzel Coulee, into which Washtucna opens, these terraces are 200 feet and more above the bottom.

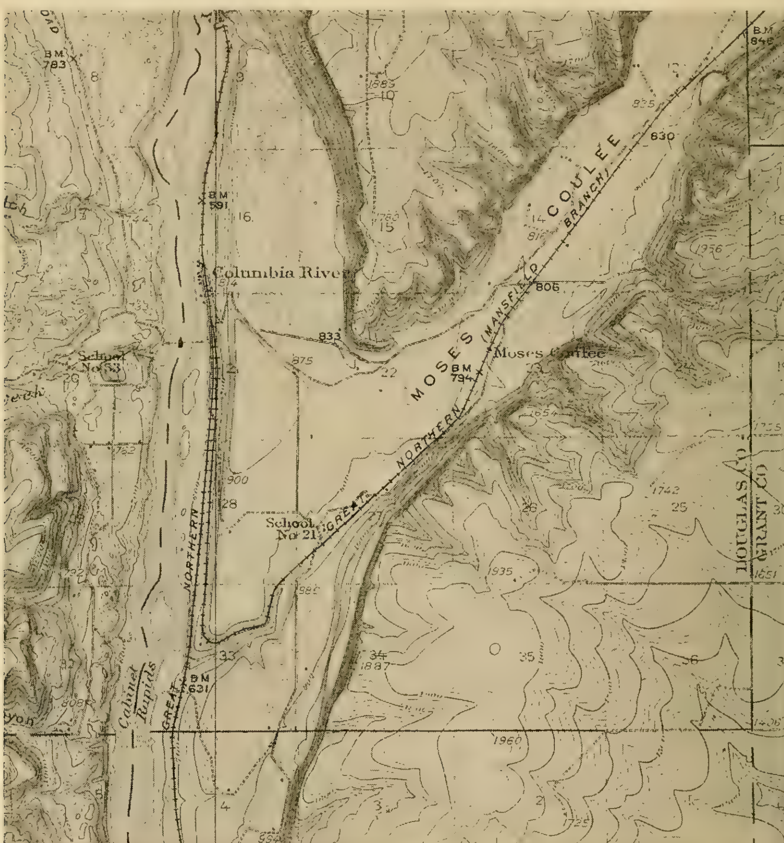


FIG. 9.—The lower part of Moses Coulee. Part of Malaga, Washington, topographic map. Note truncated spurs, hanging ravines, alluvial fans, and the great terrace in both Moses Coulee and Columbia Valley.

In Lower Moses Coulee (Fig. 9), the mouths of preglacial tributary ravines hang approximately 400 feet above the rock floor. Some of this discordance of grade is due to widening of the preglacial coulee, which here was a canyon, by the glacial stream but probably most of it is due to deepening during the glacial epoch.

In addition to the deepening of valleys already existing, the glacial flood actually made, *de novo*, drainage ways of greater width and depth than any previously developed on the plateau. This happened where divides were crossed and unusually high gradients down the farther slopes were found. Five such places are especially noteworthy: Devils Canyon, Palouse Canyon below Hooper, Drumheller Channels, Othello Channels, and Grand Coulee.

Preglacial Palouse River joined Snake River at Pasco, its subparallelism with the larger stream for 150 miles being structurally determined. The glacial flood from the north entered it in midlength at several places between Winona and Washtucna. The volume of this flood was more than the valley could carry away.

Fig. 10.—Devils Canyon, cross-section a mile and a half south of Kahlotus, showing (1) steepened loessial bluffs (33°), (2) narrow scabland above brink of basalt cliffs (3) canyon 450 feet deep and less than one-fourth mile wide, and (4) post-Spokane talus, three-fourths the height of the cliffs. Horizontal and vertical scale the same.

Two leaks across the divide to the Snake developed, one near Kahlotus, and one near Hooper, and in both very great gradients were encountered.

The Devils Canyon distributary, south of Kahlotus, cut 50 feet or so through the loess and then by recession of waterfalls over ledges of basalt in the north slope of Snake River Valley, it eroded a canyon 5 miles long, a quarter of a mile wide and 500 feet deep (Fig. 10). Every fall but the lowest retreated completely through the divide. The remaining ledge, like a dam separating the two canyons, is less than 100 feet above the floor of Washtucna Coulee and not half a mile wide.[1] An abandoned half of a double cascade stands in mid-length of Devils Canyon (Fig. 4).

[1] The Spokane, Portland and Seattle Railroad tunnels through this ledge. In 1916, Washtucna Lake was so high for a time that it overflowed through this tunnel into Devils Canyon.

A much larger volume of water spilled across the preglacial divide south of Hooper. Before the great canyoned channel now transecting this divide had been eroded, the stream was 10 to 15 miles wide. Several channels of canyon proportion were initiated, but one outran the others in its deepening and finally secured all the discharge. Many of the shallower canyons enter the southern part of the main one over abandoned waterfalls. These channels could have carried water only when the wide scabland of the divide had no deep canyon completely across it. Their falls could have developed only after a deep main canyon existed *below* their junction. It follows, therefore, that Palouse Canyon was cut by retreating waterfalls, though these were destroyed later in the epoch. One only survived, now notched considerably by the post-glacial work of the Palouse River. The falls today are 198 feet high. Palouse Canyon is another Devils Canyon in all save its greater width and the fact that the preglacial divide was cut entirely in two.

Drumheller Channels and Othello Channels are two remarkable cases where the glacial flood crossed anticlinal ranges.[1] In both, the anticline is asymmetrical and the waters flowed down the gentle slope. In both, the flood at first was wide but became concentrated later in the deepening canyons. The maximum depth of erosion in Drumheller Channels was 400 feet, about 100 feet of which was in a weak sedimentary formation (probably the Ellensburg), and 300 feet in basalt (Fig. 11). The width of the Drumheller denuded tract is about 10 miles. This particular scabland area has a more striking and more complicated development of channels and rock basins than any other on the plateau. It is the only area of this type now topographically mapped. Below the Channels, along the northern flank of Saddle Mountains, the ancient river eroded 300 feet into the broader scabland.

But Drumheller Channels is not wholly the product of the glacial flood whose history we have been following. It and the main canyon of Grand Coulee carried drainage from a later ice sheet, and it has carried Crab Creek since the later glacial epoch. The amount of deepening during each Pleistocene epoch is diffi-

[1] Drumheller Channels crosses the eastern nose of Frenchman Hills anticline, Othello Channels crosses the eastern nose of Saddle Mountains anticline.

cult to determine. Othello Channels carried less water than Drumheller Channels, consequently is a smaller tract. Furthermore, it received water during only the earlier epoch. The degree of development of its canyons and rock basins is comparable to that of the larger tract and makes it probable that most of Drumheller Channels were formed during the earlier epoch.

The features of Grand Coulee are of such magnitude and its history so complicated by local conditions that an entire paper might well be devoted to it. It affords the greatest example of canyon-cutting by glacial streams, not alone for the Columbia Plateau, but for the world. The field evidence indicates that no preglacial drainage route ever existed here. Scabland with shallow channels margins the upper part of the Coulee, though 1,000 feet higher than the adjacent coulee floor, and there are no tributaries in the mature topography such as are possessed by Lower Moses Coulee and Washtucna Coulee. A glacial river, 3 miles in minimum width, spilled southward here over the divide and down a steep monoclinal slope. Judging by present grades and altitudes of this structural slope, the stream descended nearly 1,000 feet on a grade of approximately 10°, a few miles north of Coulee City. Such a situation is unparalleled, even in this region of huge, suddenly initi-

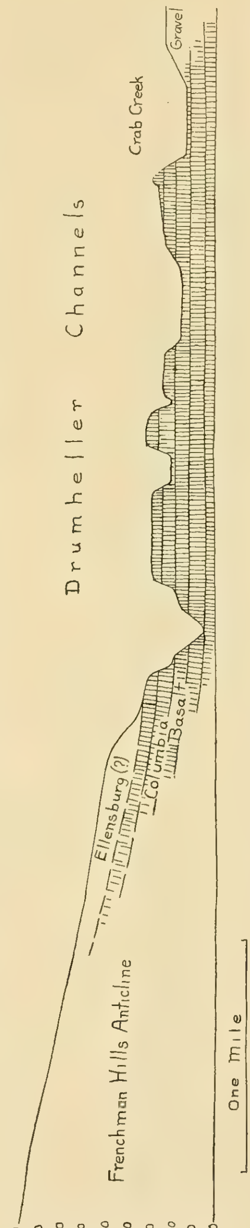


FIG. 11.—Cross-section of the head of Drumheller Channels, showing (1) structure at eastern nose of Frenchman Hills anticline, (2) the pre-scabland topography, and (3) the scabland channels. Probably no preglacial drainage crossed the anticline at this place. The lower 50 feet of the deepest channel is a rock basin.

ated, high-gradient rivers. Across this monocline between Columbia River and Coulee City, the canyon is 30 miles long and averages all of 2 miles in width and 800 to 900 feet in depth. In the making, at least 10 cubic miles of basalt were excavated and removed. Though a later flood of glacial waters used this route,[1] it did but little to deepen it.[2] By far the greater part of the erosion of Upper Grand Coulee was performed by the earlier glacial stream. It is very probable that this immense task was performed by the stoping of cascades and cataracts which retreated entirely through the monoclinal uplift to the deeper valley of Columbia River and thus left the great notch.[3]

It also seems probable that when the retreat of the ice sheet began, the plateau west of Grand Coulee was abandoned last. Earlier clearing of the Spokane and Columbia valleys to the east allowed all the drainage of the ice sheet to use the Grand Coulee route, which was then the lowest of all. Grand Coulee's greatest flood and probably its greatest erosion thus came after the other scabland routes had gone dry.

VOLUME OF THE GLACIAL STREAMS

If the channeled scablands of the Columbia Plateau are the erosive results of glacial waters, certain statements as to the volume of the streams can be made. Measurements are possible if remnants of the preglacial floor of the main valley exist in places where the valley brimmed over with the glacial flood to produce distributary courses. Should it appear that the amount of canyon-

[1] During the Wisconsin glaciation.

[2] Grand Falls, below Coulee City, consists of Dry Falls, Deep Lake Falls and a smaller unnamed falls a mile east of Deep Lake. The lip of the smaller falls is 125 feet higher than the floor of the channel leading to Dry Falls. Yet all were made by the same glacial stream and only Dry Falls and Deep Lake Falls were used and modified by the later discharge.

Furthermore, the Wisconsin ice did not cross Spokane River or Columbia River east of Grand Coulee and its waters were free to use the lowest of the ten earlier routes. Only Grand Coulee was so used, showing that it had been eroded by the earlier discharge to a depth not far short of that which it now has.

[3] This inference has no physiographic evidence in Grand Coulee to substantiate it, but is based on the known procedure of the glacial streams in similar situations, e.g., Lower Palouse Canyon, Devils Canyon, Frenchman Springs, and The Potholes.

cutting by these glacial streams has been overestimated, the depth of the stream to flood across the divide must be correspondingly increased. This view promptly runs into an absurdity, for the less the canyon-cutting is held to have been, the deeper and therefore more competent to erode the stream must have been.

One of the best cases for measurement is Washtucna Coulee at the head of Devils Canyon. Though there are but two small rock knobs out in the coulee floor, the summit of neither indicating the original valley bottom, there are good rock terraces to record it (Figs. 12 and 13). Near Kahlotus they lie 1,000 to 1,200 feet above tide. The glacial stream here, at the beginning of its history, overflowed through the loessial hills to Snake River, at an altitude of at least 1,350 feet. It was, therefore, from 150 to 350 feet deep. Its width averaged at least a mile.

And this was no ponded condition, for Washtucna Coulee opened widely into Esquatzel Coulee, an even more capacious valley, and Esquatzel in turn into Columbia and Snake valleys, and the glacial waters cut deeply into the bottom of both coulees. Figuring the preglacial floor as 1,000 feet A.T. at Kahlotus and as 675 feet A.T. at Eltopia, 34 miles farther down the valley, the great glacial stream had a gradient of about 10 feet to the mile.

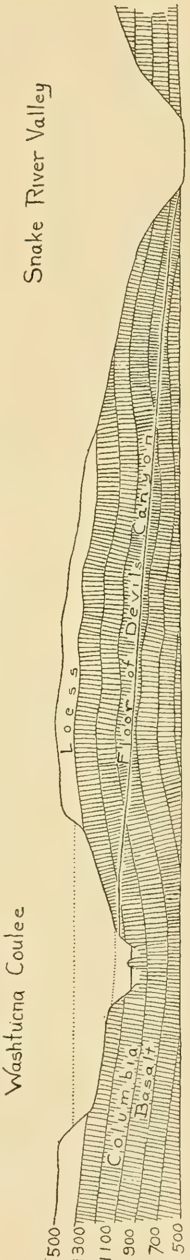


FIG. 12.—Cross-section of Washtucna Coulee and Snake River Valley, with longitudinal profile of Devils Canyon, showing (1) structure of the basalt, (2) its loessial cover, (3) rock terraces flanking Washtucna (Kahlotus) Lake, remnants of the preglacial valley floor, (4) the inner canyon eroded by the glacial stream, (5) steepened slopes of the loess, facing the coulee, and (6) approximate upper limit of the flood which spilled across to Snake River.

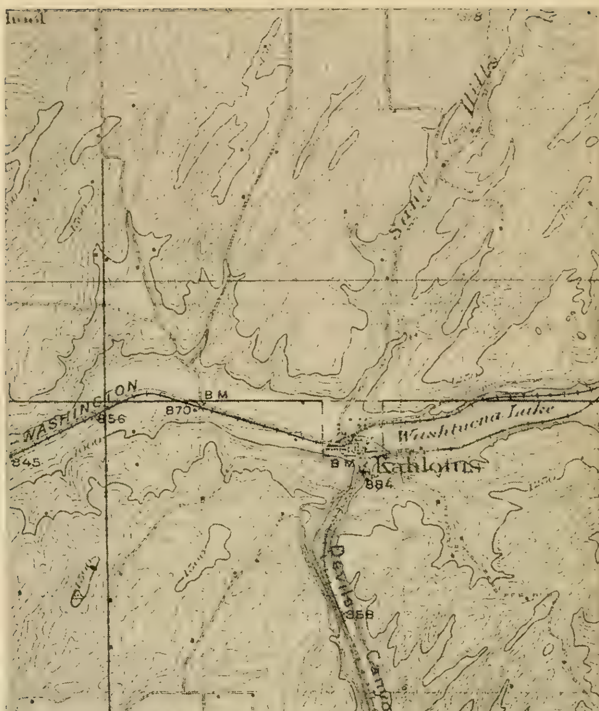


FIG. 13.—Devils Canyon. Part of Connell, Washington, topographic map.

Further evidence that glacial waters so filled Washtucna Coulee that the former valley became simply a channel is found in the upper limit of glacial stream gravels and of scablands. At the head of Devils Canyon, the highest scabland is 1,250 feet A.T., 250 feet above the brink of the cliffs of the canyoned channel. At Estes, a gravel bar deposited by the glacial stream lies 250 feet above the Coulee floor and about 125 feet above the rock terrace which marks the old valley floor. Near Sulphur, the highest scabland surface, at the base of the steep loessial bluffs, is between 1,100 and 1,150 feet A.T., 100 to 150 above the rock terrace. Northwest of Connell a terrace of sand and fine gravel lies at 1,000 feet A.T. It marks the upper margin of the scabland here and probably is a deposit of the glacial stream. It is 100 feet above the broad rock terrace. The canyoned channel here is cut 150 feet below the rock terrace.

Crab Creek Valley, below Odessa, received more water than it could carry away, at least before its central canyon had been eroded. It overflowed southwestward, by way of Black Rock Coulee and its associated scabland, to the Quincy Basin which Crab Creek itself entered farther north. Measurements here are only approximate but they indicate the order of magnitude of this glacial stream. Scabland and glacial stream gravel along the southern edge of Crab Creek Valley lie 300 feet or more above the present stream and extend a mile and a half back on the upland from the margin of the preglacial valley. This valley had been canyoned more than 100 feet by the glacial stream which, on the basis of these figures, was 200 feet deep at its inception.

The Telford scabland tract, 13 miles wide and 20 miles long, has been swept almost completely bare of the loessial deposit. The relief in a cross-section of the basalt surface now exposed, aside from the minor canyons, is about 50 feet. To have been so denuded, this tract must have had a sheet of running water of this depth completely over it.[1]

[1] That the ice sheet did not advance over the Telford denuded tract is shown by the presence of a few isolated loessial hills with characteristically steepened marginal slopes. One such group lies 7 or 8 miles north of Telford. It has a maturely eroded topography and a dark loessial soil without rock fragments of any kind. But it is cut by channels of glacial waters which eroded to the basalt. The fact that these waters went through the group, though the surface immediately north of them drops off into the deep canyons of Hawk Creek, a tributary of Spokane River, proves that glacial ice must have crowded up against the northern side of the group.

Further evidence of the depth of the glacial streams will be presented under the next subject.[1]

DEPOSITS MADE BY THE GLACIAL STREAMS

The record of Pleistocene glacial streams almost everywhere is one of aggradation. Glacialists commonly think of the subject only in such terms, textbooks discuss it only in that light; it is the orthodox conception. But in the Columbia Plateau exceptional factors controlled. The preglacial valleys in general were small and of relatively high gradient, the volume of the glacial streams was very great, the amount of detritus from the ice was very small, and the rock crossed was either loess or closely and vertically jointed basalt, both of which yielded rapidly to the torrents. The result of these conditions was great deepening of the valleys, and deposits made by the streams are of minor importance. Their character, however, adds to the weight of evidence already presented for the origin of channeled scabland by glacial stream erosion.

The deposits are almost wholly of gravel. Sand is a minor constituent and clayey material is lacking. The gravel and sand are almost wholly of basalt, though all deposits contain fragments of rock foreign to the plateau. The basaltic gravel is not well rounded though most of it is sorted and stratified and indubitably of stream origin. Foreset bedding is common, the direction of dip according with the slope of the scabland tract. In some places, the deposits are composed of very coarse material, with abundant, sub-rounded, basaltic bowlders 3 and 4 feet in diameter. These were originally bowlders of decomposition and were derived from flows with particularly large columns, underlying or in the immediate proximity of the deposit. Where a few erratic bowlders are associated[2] the deposit itself might be misinterpreted as a bowldery till.

The gravel deposits rest on irregularly eroded basalt, essentially a buried scabland surface. Nowhere do they lie on or beneath the loess. Neither the gravels nor the underlying basalt are

[1] If these enormous streams all came to the Columbia eventually, should not the great volume be recorded farther down the master stream? The writer has seen enough to convince him that it is so recorded, and hopes to publish on this subject in the future.

[2] As west of Lantz, for example.

decayed.[1] Cementation with calcium carbonate has begun but has not advanced far.

Most isolated loessial hills in a scabland tract have a deposit of gravel depending from their down-gradient end. Many knobs and buttes of basalt have similarly situated gravel deposits.

In many cases, the gravel deposits constitute discontinuous terraces on the margins of the scabland tracts, suggesting remnants of former valley fills.[2] But the evidence seems conclusive that all gravel deposits of the scablands are bars, built in favorable situations in the great streams which eroded the channels.

The rounded profiles and ground plans of many gravel deposits in the scablands are in accord with this interpretation. The unfilled canyons and rock basins, in intimate association with the discontinuous gravel deposits, indicate clearly that both are products of the same episode. The only alternative hypothesis is that channeled scabland was formed, then buried in gravel, then in large part re-excavated by streams little short of the magnitude of those which eroded the scablands. This has no other field evidence to support it and requires a much more complicated history. Furthermore, such deep canyons were cut when the scablands were made, and such noteworthy divide crossings were made that a reoccupation of all the scablands by glacial drainage from a second ice sheet would be impossible. And the hypothesis of dissection by the postglacial streams of the scablands is quite inadequate. Lakes and pools still stand in the rock basins on the channel floors, almost as they were left by the glacial flood.

Gravel deposits in the deeply canyoned scablands occur on the broad upper scabland surfaces, on the roughened slopes of the preglacial valleys and down in the canyons. The interpretation of these deposits as bars requires no change in general conditions, as does the alternative hypothesis; it simply requires that gravel be deposited locally as conditions might favor, all through the

[1] Local exceptions, as 1 mile southwest of Lamont, where ground water has been especially active.

[2] So the terraces in Pine Creek channel were interpreted in the earlier paper by the writer. That view is here abandoned for one much more consistent with all other features of the scablands.

epoch of erosion of the basalt. Deposits on the highest scablands[1] were made before the deepening canyons drew the waters into more restricted routes. Deposits in the deeper portions[2] were made during the latest stages of the episode. No gravel deposits were ever as thick as the rival hypothesis would require them to be.[3] That view demands that the canyons be eroded, then filled completely *with their own débris*, then re-excavated in large part.

However, there are two places on the plateau where the history of deposition by glacial streams has been somewhat different. One of these is Hartline gravel flat, the other is Quincy Basin. Both are structural depressions, not completely filled before the glacial floods arrived. The Hartline structural valley became filled with débris from the cutting of Upper Grand Coulee before Lower Grand Coulee had been eroded. The trenching of the lower coulee, and particularly the development and retreat of Grand Falls, incised the southern rim of the valley so that, by the close of the episode, the gravel fill, once the floor of the glacial stream, had been removed in its western part, and the remnant left 200 feet or so higher than the brink of Grand Falls.[4] The total fill in the Hartline structural valley is about 250 feet. It is composed of bowlders, cobbles, and gravel near Grand Coulee, and of sand 5 or 6 miles east, back from the main drainage line. An old channel from Grand Coulee crosses its northern and eastern part and leads into Deadmans Gulch, a distributary which spilled across the southern rim into Spring Coulee before Lower Grand Coulee had developed into the dominant notch that drained and dissected the flat. The terrace form of Hartline flat is the result of erosion of a once complete gravel fill. Its scarp is not constructional, as are those of bars. But the fill and the subsequent erosion occurred because of special local conditions, not because general conditions changed.

[1] As about Gloyd along the Black Rock distributary from Crab Creek Valley.

[2] As at the mouths of Duck Creek and Wilson Creek in Crab Creek Valley and at the junction of Crab and Coal creeks.

[3] For example, gravel deposits north of the town of Washtucna lie on the slopes of the coulee, 350 feet above the present floor. They antedate the deeper canyoned portions of the coulee.

[4] Estimated from the surviving eastern member of that complex waterfall, the only part which escaped modification by the Wisconsin glacial stream.

Quincy Basin, like the Hartline Valley, does not have a scabland floor. Both lay too low to be eroded. But both belong to the glacial drainage plexus. Quincy Basin probably contains more gravel than all the scablands of the plateau together. It was an enormous settling basin for the glacial rivers from Grand Coulee and Crab Creek. The flood of waters entering it was so great that at first three discharge ways were simultaneously in operation.[1] The southern and larger one obtained all the discharge later, and by deep notching of the basin's rim, caused the glacial waters which traversed the fill to incise their deposits. Two great channels and one smaller one were thus formed. The two large channels are each about 3 miles wide. Each was eroded about 100 feet deep during the later part of the episode. The one which contains Rocky Ford Creek also carried the later Wisconsin discharge and was further modified then.[2]

Erratic bowlders, some of them striated, are widely distributed at all altitudes on the basalt plain and the scablands. They also occur in valleys of the mature topography which open northward on to the basalt plain, and in some which open on to scabland tracts. The size, angularity, and striated surfaces indicate that these erratic bowlders were not rolled to their positions by running water. In the scablands, they must have been carried by berg ice on the great rivers. In their peculiar and limited distribution in the valleys in loess is evidence of small glacial lakes, in which the drift-bearing bergs floated.[3]

[1] Frenchman Springs, The Potholes, and Drumheller Channels.

[2] This interpretation is a modification of that published earlier by the writer. Further study of Grand Coulee, Quincy Basin, and Drumheller Channels has led to a magnification of the work of the earlier flood, and a minimizing of the results accomplished during the Wisconsin epoch. Grand Falls is now considered to be a pre-Wisconsin affair, none of the distributary canyons of Grand Coulee, except Dry Coulee, are thought to have functioned during the second flooding, the Adrian terrace is considered to be a part of the original fill and not of Wisconsin age, and all the deep canyons of Drumheller Channels are thought to date back to the earlier episode.

[3] Below an altitude of about 1,250, erratic bowlders occur on every formation and type of topography on the plateau. But these are a younger deposit (see *Journal of Geology*, Vol. XXVII [1919], pp. 489–506) and do not much overlap the scablands. Where overlap does occur, however, it is impossible to distinguish bowlders of the two categories by any difference in the amount of decay.

DEPTHS OF SNAKE AND COLUMBIA VALLEYS DURING THE EPOCH

Evidence on this question may be obtained at the debouchure of glacial drainage routes into these master valleys. Five of the nine such debouchures will be examined.

The rock floor of Moses Coulee is fully as low as that of Columbia Valley at the junction of the two. Both contain a great gravel fill here. Columbia River has cut through it, a depth of more than 300 feet. There is no such trenching in Lower Moses Coulee, but a well at Appledale penetrates 300 feet of this gravel without encountering bedrock.

The two cataracts of The Potholes and Frenchman Springs, which operated in the early part of the epoch, descended nearly the full height of the present Columbia Valley walls there. At The Potholes the glacial cataract can be traced down to less than 200 feet above the present Columbia (Fig. 7).

Koontz Coulee, 20 miles north of Pasco, is cut in the weak Ringold formation. It is 250 feet deep and a mile wide. It is floored with basaltic stream gravel from the scablands farther upstream. Though the Ringold silts extend down to the level of the Columbia at this place, the mouth of the glacial river channel hangs 200 feet above. No cataract could have been maintained here, as was done at The Potholes and Frenchman Springs, and the level of the Columbia of this epoch at this place is thus clearly recorded.

At the mouth of Palouse River, there are two parallel canyons in the scabland, one containing the river, the other dry. A basaltic butte separates them. It stands nearly in the center of the valley and its summit is between 350 and 400 feet above Snake River. It is a part of the original north wall of Snake River Valley, over which the gigantic cascade tumbled when the glacial flood broke across the preglacial divide from the north. This "Goat Island" testifies to the existence of a Snake River Valley at this place as deep then as now.

THE GLACIATION

Because the record of the ice sheet, from which came the streams that made the scablands, is best preserved on the basalt plain about the city of Spokane and along the south side of Spokane River,

this has been named the Spokane glaciation.[1] It assuredly is not an early phase of the Wisconsin glaciation. That is recorded by pronounced moraines on the plateau west of Grand Coulee, in Columbia Valley north of the mouth of Spokane River, and in Colville Valley north of Spokane River. The Spokane ice left no terminal moraine and very little ground moraine. The reverse relation exists regarding the glacial waters of the two glaciations, for the Spokane glacial waters were of prodigious quantity and the Wisconsin waters of little consequence. Furthermore, a long time elapsed between the two glaciations as shown by the relative volume of talus accumulations in tracts swept by glacial streams of the two epochs. Post-Spokane talus in almost all places stands three-fourths to four-fifths of the total height of the basalt cliffs, post-Wisconsin talus stands about halfway up on the cliffs of Grand Coulee.[2]

For the absence of a terminal moraine along the southern edge of the area reached by the Spokane ice sheet, the writer has as yet no satisfactory explanation. It seems clear, however, that a moraine never was deposited, rather than that it was once built and subsequently removed. The functioning of some scabland tracts absolutely required glacial ice against the north slopes of the unglaciated hills at their heads. Floated granite erratics among some of these hills also require blocking of valleys by glacial ice. Yet there is no evidence of lateral drainage along the ice front in contact with the unglaciated hills, to which might be ascribed the removal of a terminal moraine.

The Spokane glaciation cannot be dated very far back in the Pleistocene, else the scablands should have a soil mantle of eolian sand and dust and disintegrated basalt, and the hundreds of lakes in the old channels should have been destroyed.

Leverett has suggested that a pre-Spokane till beneath loess at Cheney is of Kansan age.[3] If it is, and if the post-Spokane glaciation is correctly ascribed to the Wisconsin epoch, the Spokane

[1] J H. Bretz, "Glacial Drainage on the Columbia Plateau," *Bulletin of the Geological Society of America*, Vol. XXXIV (1923), pp. 573–608.

[2] This question of differentiating Pleistocene epochs by talus accumulation will be discussed more fully in a separate paper.

[3] Frank Leverett, *Bulletin of the Geological Society of America*, Vol. XXVIII (1917), p. 143.

glaciation should be either Iowan or Illinoisan in age. Farther than this, the writer does not care to go. Ordinary criteria in use east of the Rocky Mountains for differentiation of drift sheets cannot safely be used for the correlation of these glaciations in Washington. The only one relied on here is the moraine-building habit of the Wisconsin ice sheet, a character which seems to have been world-wide.[1]

There were no channeled scablands on the Columbia Plateau before the Spokane glaciation. A mantle of loess, with a mature topography, completely covered it. The evidence for this conclusion is found in the great and remarkably persistent width of the Cheney-Hooper scabland tract throughout a length of 70 miles, and the various distributary courses out of it, some of which never were eroded to the basalt. These features never could have been formed, had spillways like those of the present existed. But with early escape southward retarded by the loessial hills and their small drainage ways, a wide spreading among them necessarily occurred, and some distributaries were able to cross to Crab Creek drainage.

A puzzling situation regarding glacial drainage exists in the vicinity of the small Spangle lobe. There is no adequate drainage route around it for glacial waters which came from Idaho and western Montana and entered the Cheney-Hooper scabland tract. Two spillways exist north of Mica, between Lake Spokane[2] east of this lobe and Pine Creek channel. Both have erratics in them, the highest at 2,550 feet A.T., but neither carried much water. There is no error involved in mapping this lobe because an ice dam at Spangle is required for the operation of the Pine Creek channel. This channel carried far more water than the Mica spillways, water derived directly from the Spangle lobe. Yet it also is inadequate for the drainage in question. And much more water went down the Cheney-Hooper scabland tract, in proportion to the immediately tributary ice edge, than passed through any other

[1] No till or other evidence of pre-Spokane glaciations has been found beneath the loess (save only the Cheney deposit). No till has been found in the scablands. The writer is unable to agree with J. T. Pardee who states (*Science*, Vol. LVI [December 15, 1922], pp. 680–87) that till occurs at "scores" of places on the plateau south of the limit of Spokane glaciation, as mapped in Plate III.

[2] Thomas Large, *Science*, Vol. LVI (September 22, 1922), pp. 335–36.

scabland tract except Grand Coulee in its later stages. It seems necessary, therefore, to assume a prominent *subglacial* drainage line, across the area covered by the Spangle lobe. This is best located along the preglacial valley of Lake (Marshall) Creek and the rock basin of Farrington (Fish) Lake. Out of this rock basin, just beneath the edge of the ice, the waters from the east emerged and joined those coming directly from the ice.

If the battle between the diluvialists and the glacialists, out of which has emerged our conception of Pleistocene continental glaciation, had been staged in the Pacific Northwest instead of the Atlantic Northeast, it seems likely that the surrender of the idea of a debacle might have been delayed a decade or so. Fully 3,000 square miles of the Columbia plateau were swept by the glacial flood, and the loess and silt cover removed.[1] More than 2,000 square miles of this area were left as bare, eroded, rock-cut channel floors, now the scablands, and nearly 1,000 square miles carry gravel deposits derived from the eroded basalt. It *was* a debacle which swept the Columbia Plateau.

[1] Except in the Hartline and Quincy structural depressions.

ALMANDITE AND ITS SIGNIFICANCE IN THE CONTACT ZONES OF THE GRENVILLE LIMESTONE[1]

GEORGE W. BAIN
Columbia University

INTRODUCTION

The highly metamorphosed rocks of the Grenville series have attracted intense interest ever since Sir William Logan gave them a name and a place in geological literature. In view of the great wealth of geological information obtained from these old crystallines it would seem that they have nothing new to give to the science of geology and mineralogy, yet every time they are studied they yield some piece of information. The present article deals with one mineral, almandite, its origin, alteration, and instability. These changes are involved in the intense contact action produced by the great Laurentian Batholith.

LOCATION

The area which was studied previous to preparing this paper lies in Chatham Township, four miles northwest of the town of Lachute on the North Shore branch of the Canadian Pacific Railway 44 miles west of Montreal. The district is on the very edge of the Laurentian Highlands and the swift streams have cut moderately deep valleys for a short distance back from the broad fertile plain of the Ottawa Valley (Fig. 1).

GENERAL GEOLOGY

The rocks of Chatham Township are chiefly old crystallines, in part intensely metamorphosed sediments of early Precambrian

[1] The chemical and petrographical studies undertaken previous to preparing this paper were carried out at Columbia University under the guidance of Prof. J. F. Kemp, Dr. C. P. Berkey, and Mr. R. J. Colony to whom the writer is greatly indebted for assistance, advice, and helpful criticism.

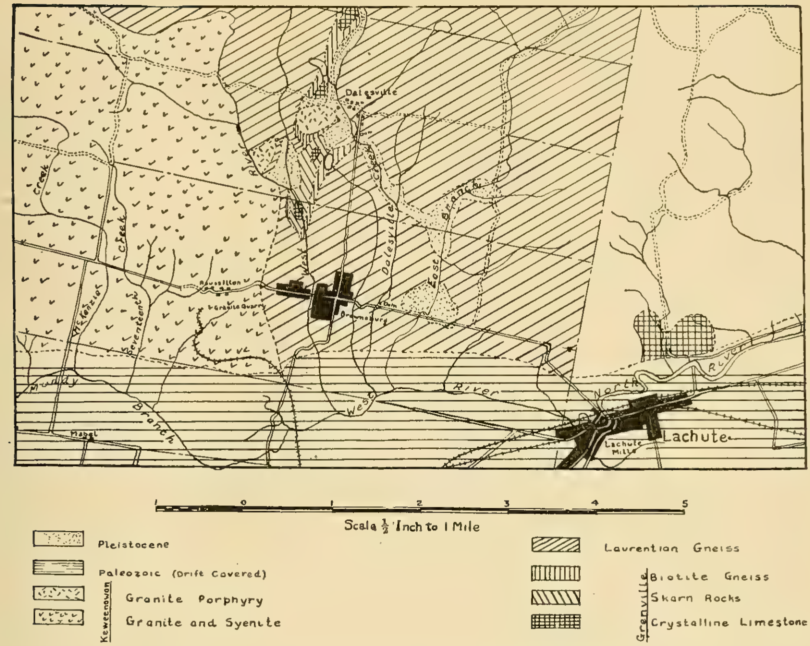


FIG. 1.—Map of the Grenville Series and related rocks of Chatham Township.

age, but mainly large intrusive batholiths of granite. Glacial débris of the Pleistocene ice sheet is strewn over the surface.

Pleistocene	Lake deposits Ground moraine
Keewenawan	Trap and microgranite Granite porphyry Granite and syenite Granodiorite Diabase
Laurentian	Granite Aegerite granite dykes Peridotite and pyroxenite
Grenville Series	Limestone

In this complex only the Grenville series and the Laurentian granite are of interest in this paper.

THE GRENVILLE LIMESTONE

The Grenville limestone is a blue, coarsely crystalline limestone composed of about 1 per cent of dolomite, 15 per cent of wollastonite

and diopside, and the remainder calcite. Minor amounts of phlogopite, garnet, chondrodite, scapolite, and sulphides are also found locally, but their occurrence is always such as to suggest introduction by magmatic emanations from the granite. An inclusion of blue limestone in an aegerite granite dyke of early Laurentian age gave the following analysis:

	Per Cent
Diopside and Wollastonite	16.4
Soluble Iron and Alumina	2.2
Calcite	81.0
Dolomite	1.1
	100.70

(The carbonates are given as dolomite and calcite rather than as dolomite or as calcite and magnesite, because when the polished surface of a specimen was treated with Lemberg's solution, it was found that the rock consisted of two definite carbonates, the one being calcite, and the other, in an amount demanded by the dolomite ratio, determined by a chemical analysis.)

Since this fragment of limestone was sealed off from all outside sources of material before the contact effects of the granite became pronounced, it is believed to represent very closely the composition of the original limestone; slight additions of silica from the dyke may have been received. On the other hand, since the dyke itself is somewhat pegmatitic, the limestone may have undergone mild contact-metamorphism before being effectually sealed away.

Away from the dyke the limestone has come under the influence of magmatic waters which have produced considerable silication. A typical analysis of the silicated limestone is as follows:

Proximate	Per Cent	Ultimate	Per Cent
Wollastonite and diopside	30.00	SiO_2	16.05
Soluble iron and alumina	0.25	Al_2O_3	0.14
Calcite	69.62	Fe_2O_3 / FeO	1.54
Dolomite	0.15		
		CaO	46.65
		MgO	5.25
		Na_2O	.....
		K_2O	.....
		CO_2	30.80
			100.43

THE SKARN ROCKS

When this bed is followed along the strike for about 600 feet it changes to a rock composed of:

	Per Cent
Diopside, Wollastonite	47
Phlogopite	few flakes
Calcite, Dolomite	45
Pyrrhotite	2
Magnetite	1

After a short distance the bed comes under greater influence of solutions from the batholith and changes over to a skarn rock composed of:

	Per Cent
Orthoclase, Andesine	75
Almandite	10
Pyroxene	4
Calcite, Dolomite	8
Phlogopite	1
Magnetite, Pyrrhotite	2

At this point the bed passed beneath a thick cover of drift and the more advanced stages, which are of chief interest in this discussion, had to be studied in another locality where the succession was more complete. The locality chosen was at Campbell's Dam near Dalesville, where excavations had been carried on to some extent in preparing the base for a waterwheel. At this point the limestone was observed to change quite rapidly to a skarn rock containing larger garnets in greater abundance than in the former locality. Both the skarn rock and the garnets were analyzed and the results are reproduced below.

	Garnet Rock Per Cent	Garnet Per Cent	Garnet Per Cent
SiO_2	53.10	41.15	41.33
Al_2O_3	24.38	20.60	20.77
Fe_2O_3	2.86	Tr.	Tr.
FeO	11.21	30.09	30.05
MnO	Tr.	Tr.	Tr.
CaO	1.16	2.41	2.37
MgO	2.40	5.73	5.67
Na_2O	2.94	.....	.....
K_2O	1.49	.....	.....
H_2O	0.60	.....	.....
	100.05	99.98	100.19

In addition to garnet the rock contains numerous grains of magnetite and stringers of clear quartz. Feldspars are also abundant.

THE BIOTITE GNEISS

When the garnet zone is followed along the strike for any distance it passes into a biotite gneiss. Thin sections of this gneiss were examined and the rock was seen to contain about:

	Per Cent
Biotite	15
Quartz	25
Chlorite	15
Orthoclase	12
Andesine	15
Almandite	5
Sillimanite	3
Carbonates	3
Sericite	2

The garnet is heavily fractured and elongated in the plane of schistosity. Along these fractures it has altered to a green chlorite which itself is recrystallizing to form biotite. The sillimanite exhibits a change similar to that taking place in the garnet.

Both the biotite gneiss and the biotite of the gneiss were analyzed. The results of the analyses are given below:

	Biotite Per Cent	Biotite Gneiss Per Cent
SiO_2	36.93	55.91
Al_2O_3	22.32	18.44
Fe_2O_3	15.53	2.37
FeO	1.41	7.42
CaO	2.73	3.50
MgO	9.22	3.61
MnO	Tr.	Tr.
K_2O	3.07	1.13
Na_2O	3.12	2.08
CO_2, H_2O, F	4.68	4.74
	99.01	99.20

When the biotite gneiss is studied as a rock rather than as a petrographical curiosity, it is seen to be cut by innumerable pegmatite dykes which are connected with the Laurentian granite. These pegmatites have soaked the biotite-bearing rocks and it is almost inconceivable but that they must have added silica, a lumina, and alkalies to the original.

THE GRANITE GNEISS

To complete the discussion of the contact zones and the alteration of the almandite, it is necessary to include an analysis of the granite gneiss. Although this analysis is given in *The Superior Analyses of Igneous Rocks*, it is not typical of the Laurentian granite but rather of the granite gneiss, which is a complex or hybrid rock distinguishable from the granite by a higher percentage of ferro-magnesian minerals and a strong gneissic structure. The granite itself contains practically no ferromagnesian minerals and has at best a very poor streaked appearance when free from roof pendants of gneiss.

	Granite Gneiss* Per Cent
SiO_2	59.89
Al_2O_3	17.70
Fe_2O_3	1.95
FeO	2.71
CaO	2.53
MgO	1.56
MnO	....
K_2O	5.83
Na_2O	5.74
TiO_2	0.96
P_2O_5	0.17
CO_2	0.39
H_2O	0.29
	99.92

Analyst: Dittrich

* Annual Report of the C.G.S., Part O, 1899.

THE ZONAL ARRANGEMENT OF THE ROCK TYPES

The field relations show a zonal arrangement of rock types brought about by pegmatitic influences of the Laurentian granite on the Grenville limestone. The zonal arrangement is as follows:

Crystalline Limestone
|
Diopside, Wollastonite Skarn Rock
|
Feldspar, Garnet Rock
|
Biotite, Garnet Gneiss
|
Biotite Gneiss
|
Granite

In the field work, care was exercised in following the same bed, and where it was necessary to change from one bed to another the new one was picked up where it was almost identical with the one being studied. The changes outlined may be taken to represent the metamorphism of an average piece of Grenville limestone.

COMPOSITION CHANGES DURING METAMORPHISM

For the purpose of studying the metamorphism that has taken place, it is advantageous to recalculate all the ultimate analyses to molecular proportions. Molecular proportions are calculated by dividing the percentage weight by the molecular weight and multiplying by 1,000 to dispense with decimal points. The advantage of molecular proportions over percentage weights is that in chemical reactions, to form definite mineral compounds, a definite number of molecules of one oxide combine with a definite number of molecules of another. If the relative number of molecules of each oxide present is known, it is an easy matter to see the changes that have taken place. Although the results could not be recalculated with accuracy to mineral percentages on account of the mineral complexity, the method was deemed advisable in order to adhere more closely to the chemical principles in distinguishing recrystallization from replacement. Where simple minerals such as biotite and garnet are discussed, this method can be applied with obvious advantage.

Since the changes in the rock are indicative of the conditioning agencies, it is desirable to discuss them at some length before proceeding to discuss the changes in the garnet. The analyses of all the rocks recalculated to molecular proportions is given below:

	Limestone	Garnet Rock	Biotite Gneiss	Granite Gneiss
SiO_2	266	880	929	993
Al_2O_3	1	239	180	173
Fe_2O_3	9 (Fe₂O₃ and FeO together)	18	15	12
FeO		156	103	38
CaO	832	21	62	45
MgO	137	60	90	39
Na_2O	0	47	34	62
K_2O	0	16	12	92

From the analyses it will be seen that the change is in the direction of equilibrium with the granite. For the purpose of calculating the additions and subtractions, some constituent of the

original rock must be considered to remain behind throughout all the changes. Alumina seems to fill this place to perfection, since once it is precipitated it seems to migrate again only under extreme conditions, such as resolution in a batholithic magma and discharge in pegmatites. Some additions of alumina may occur but their effect will be pointed out later.

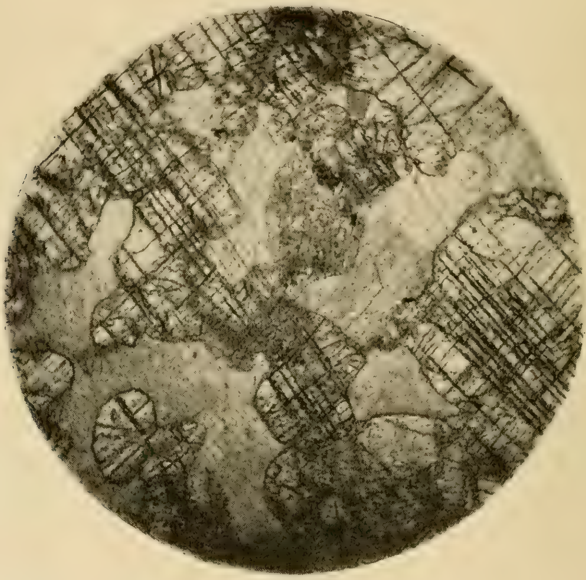


FIG. 2.—Highly silicated limestone. (Magnification about 30 diameters. Ordinary light.) The photograph shows the initial development of metapoikilitic structures with increasing amounts of diopside and wollastonite (strong cleavage). The cloudy area near the center of the field represents a pseudoeutectic intergrowth of dolomite and calcite. Calcite forms the remainder of the field.

Consider first the change from limestone to garnet rock (Figs. 2 and 3). Then since the garnet rock is formed from the limestone, replacement of the latter must continue until there are 239 times as many molecules of alumina as before. If the garnet rock was formed by simple recrystallization of the limestone, the difference expressed in the difference column would remain unadjusted and the excess material would then have to be removed in solution and would produce a great decrease in volume. But all field evidence points to practically no change in volume in this rock.

		Limestone $\times\frac{239}{1}$	= Garnet Rock	Difference
SiO_2	266	= 63574	880	−62694
Al_2O_3	1	239	239	0
Fe_2O_3	9	2151	18	−1977
FeO			156	
CaO	832	198848	21	−198827
MgO	137	32743	60	−32683
Na_2O	0	0	47	47
K_2O	0	0	16	16

The change from limestone to garnet rock involves a loss of everything but alkalies. Much of the lime and magnesia has been removed in solution and carried into the upper zones which are now

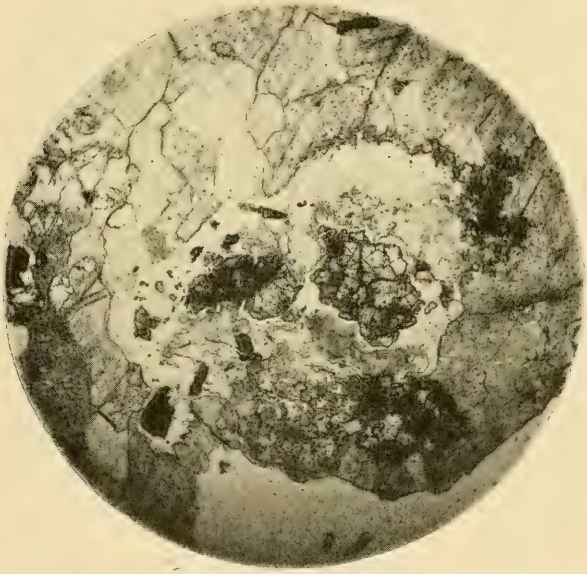


FIG. 3.—Garnet in limestone. (Magnification about 30 diameters. Ordinary light.) The photograph shows garnet (high relief) in the center of the field; it is surrounded by a broad kelyphite rim, which seems to be an incipient stage in its formation. The remainder of the field is largely carbonates.

eroded away. The apparent loss of iron and silica is due to replacement of the lime and magnesia by these constituents. From chemical analyses alone it is difficult to follow the changes, since an addition in one rock has the same effect as the loss of the same

constituent in another. Relative changes only can be determined from the composition, so that in the following interpretations the direction of the changes is based upon microscopic study and the quantitative relationships obtained from the chemical analyses.

In the garnet zone the structure indicates that lime and magnesia went into solution and were replaced by silica, alumina, and iron

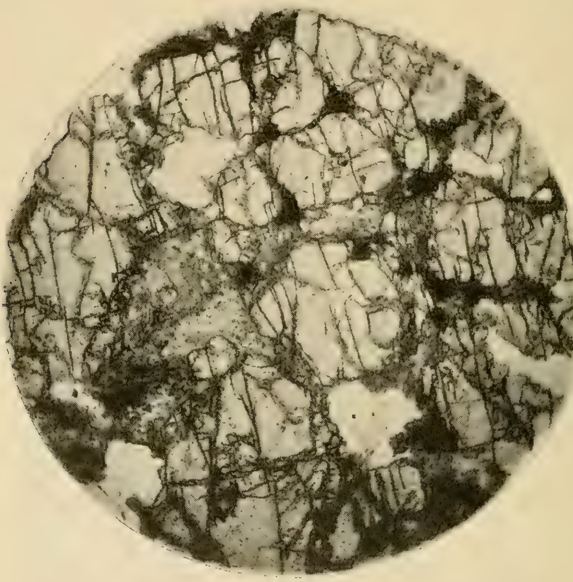
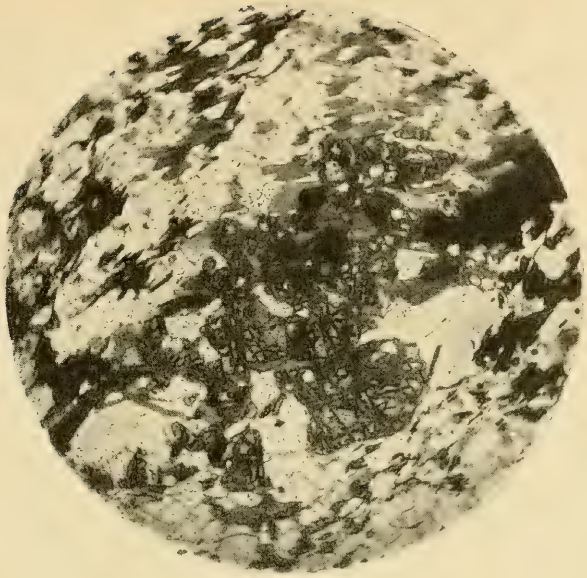


FIG. 4.—Garnet from garnet feldspar skarn rock. (Magnification about 30 diameters. Ordinary light.) The photograph shows the garnets traversed by two sets of fractures, the one more prominent than the other. The clouded areas are feldspar and the clear colorless areas quartz. The black opaque spots are magnetite.

in the form of garnet and feldspar. Selective solution and precipitation have doubtless played an important part, but the exact amount of each cannot be determined in as close a manner as in the succeeding zones. The high differences simply indicate almost complete replacement as being the dominant process in this zone as compared with dominant recrystallization in those following (Fig. 4).

Consider the change from garnet rock to biotite gneiss (Fig. 5, *A* and *B*). In this case the change is not so great; replacement



A

B

FIG. 5, *A* and *B*.—Biotite garnet gneiss. (Magnification about 30 diameters. Ordinary light.) The photograph (*A*) shows the garnets traversed by two sets of fractures one of which is parallel to the schistosity. The dark areas along the fractures are chiefly chlorite. The lighter colored dark areas, the location of which is indicated on the diagram (*B*), some of which are very minute and parallel to the schistosity, are biotite.

doubtless plays an important part, but the dominant processes are granulation and recrystallization with increase in rock volume as shown by the change of garnet and sillimanite to chlorite (Fig. 6).

FIG. 6.—Biotite gneiss. (Magnification about 30 diameters. Ordinary light.) The photograph shows a great abundance of biotite (dark) and a complete absence of garnet due to the completion of the alteration. A single elongated prism of sillimanite occurs in the center of the field. Along the cleavages it is altered to chlorite (dark). The rectangular outline at the end of the prism is a basal section of sillimanite altered to chlorite.

As before, the alumina of the original rock is assumed to remain behind and additions and subtractions of the other constituents to occur to produce the required changes.

	Garnet Rock	= Biotite Gneiss	$\times\frac{239}{180}$	= Difference
SiO_2	880	929	=1235 =	355
Al_2O_3	239	180	239	0
Fe_2O_3	18	15	20	2
FeO	156	103	137	−19
CaO	21	62	82	61
MgO	60	90	120	60
Na_2O	47	34	45	−2
K_2O	16	12	16	0

The change involves a gain in silica, lime, and magnesia and a loss of ferrous iron and soda. In this case the change in each constituent, with the exception of silica, is small. If complete replacement had occurred, the difference ought to have been infinity and, by analogy, rocks involving smaller differences in composition ought to be regarded as due to recrystallization of the minerals of the preceding zone with smaller changes brought about by replacement and addition.

Now since there has been an increase in lime and magnesia in the biotite gneiss, it must have been supplied either by the next zone nearer to the batholith or allowed to pass through that zone in solution because it did not require so much magnesia and lime to maintain a state of equilibrium. Consequently the granite gneiss ought to show an impoverishment of these constituents and the silica might also show a decrease, although that would not necessarily follow because of the intense pegmatitization. Suppose the composition changes of granite gneiss are examined.

	Biotite Gneiss	= Granite Gneiss	$\times \frac{180}{173}$	= Difference
SiO_2	929	993	= 1033	104
Al_2O_3	180	173	180	0
Fe_2O_3	15	12	12.5	−2.5
FeO	103	38	40	−65
CaO	62	45	47	−15
MgO	90	39	41	−49
Na_2O	34	62	65	31
K_2O	12	92	96	84

The granite gneiss is highly impoverished in lime and magnesia, while the additions of silica have decreased somewhat over the amount being introduced into the preceding zone.

Throughout the calculations the alumina has been assumed to remain constant in the original rock and the changes to occur by replacement of the other components. Such condition may be seriously questioned since the volume of the biotite gneisses has been increased somewhat over 15 per cent by the direct injection of pegmatite dykes. A corresponding increase might also be expected to occur through simple soaking of the rocks by pegmatitic juices. When the analyses, however, are recalculated on the assumption of an increase of from 15 per cent to 20 per cent in alumina, the only change is the establishment of equilibrium of the iron oxides;

that is, the amount of iron oxide remains constant in the rock. The alumina however accumulates above an amount required to maintain an equilibrium, and when this condition is attained, some alumina and iron oxides are held by the pegmatitic solutions, which transport them to a zone where lack of equilibrium exists. This happens to occur where the stresses in the rock are such as to permit the formation of garnet and feldspar, that is the stress on the crystal is essentially static load. The available iron and alumina combine with sufficient silica to form almandite. Magnesia and lime also enter into the combination to form grossularite and pyrope molecules. Some of the remaining available alumina combines with the alkalies and lime to form feldspars while a small amount is carried into the limestones to form mica and other aluminous minerals.

THE DESTRUCTION OF THE GARNET ZONE

As soon as the garnet feldspar zone has formed, the batholith is free to extend its activity farther into the limestone. Lateral stresses caused by mountain folding, igneous activity, and increase in rock volume produced fracturing in the garnet which then became overwhelmed in a zone in which it was unstable. Stress from one direction causes the almandite to break down into chlorite when in the presence of the circulating magmatic waters. The chlorite readily recrystallizes to biotite under the influence of these alkaline solutions.

For the purposes of studying the alteration of the garnet, the composition of both the mica and the garnet have been recalculated to molecular proportions. (In the case of the garnet it will be noticed that the material used was not entirely freed from the quartz stringers which cut the almandite and which in ordinary light look very much like it.)

	Garnet	Biotite
SiO_2	685	613
Al_2O_3	201.5	219.5
Fe_2O_3	...	14.8
FeO	419	19.6
CaO	42.5	48.7
MgO	142	228.5
Na_2O	...	50.3
K_2O	...	39.3

The change in composition shows quite clearly the effects of magnesia bearing alkaline solutions. Apparently these found easy channels along the fracture planes of the garnet where alteration is most intense.

If the garnet is corrected for the amount of quartz, which appears to be high in the molecular proportions but is really very small, the molecular composition would be:

	Garnet	Biotite	Difference
SiO_2	603	613	10*
Al_2O_3	201.5	219.5	18*
Fe_2O_3	...	14.8	385
FeO	419	19.6	
CaO	42	48.7	5.7*
MgO	142	228.5	86.5
Na_2O	...	50.3	50.3
K_2O	...	39.3	39.3
H_2O, F	...	292.0	292.0

* These differences are so small that they might readily arise through errors in sampling and in analysis as well as other variations which cannot be guarded against. For these reasons they cannot be regarded as a part of the changes during the reaction.

The F_2O_3 and FeO of the biotite are grouped together, the only significance of the ferric iron being that it indicates a very slight oxidation which, although showing in the mineral, does not occur so prominently in the rock. The outstanding differences then are the replacement of the ferrous iron by MgO, Na_2O, K_2O, H_2O, and F. Although replacement has increased the number of molecules by almost exactly one-third, which is a remarkable feature, it does not seem that the reaction could be due to simple reorganization. All of the variables are divalent and with the exception of hydroxyl and fluorine are chemically positive elements. The definite 2–3 ratio between the positive elements, alkalies and magnesia, and the negative elements, hydroxyl and fluorine suggests that a rather definite hydrated chemical compound had replaced the FeO during this reaction. If such is the case, the compound was one of the solutes in the highly heated emanations from the granite magma. Whether the fluorine and water existed separate at the existing temperature and pressure is unknown, but the oxidation of the

ferrous iron in the garnet would seem to indicate that some reaction similar to that given below had taken place:

$$2(H_2O+2F)=4HF+O_2$$
:---Nascent oxygen.
$$4FeO+O_2=2Fe_2O_3$$
From garnet-: :-----In biotite containing F.

Some reaction giving this final result does take place, and since the entire oxidation that is transpiring in the rock accompanies this change which involves the fluorine, it would seem that the above condition represents the instability in this zone. If this is correct the reaction represents the critical point above which water and fluorine can exist together as definite and distinct components.

The increase in volume caused by this reaction (the change of almandite to biotite) must have developed a pressure normal to the fractures in the garnet so that where the chlorite recrystallized to biotite the mica flakes are elongated along a certain plane to produce schistosity in the rock. Two directions of fracture are present in the garnet, one parallel to the schistosity and another at right angles to it. The chlorite along the fractures parallel to the schistosity seems to have recrystallized more readily than along the fractures at right angles to it. Fracturing in the garnet seems to have been caused by folding of the Grenville series; thus the planes of schistosity and the banding of the gneisses produced by lit-par-lit injection are controlled by the direction of the axes of the folds of the Grenville series. Migration of the biotite along the planes of schistosity, for short distances, has taken place in some cases, owing to the strong tendency of the biotite to crystallize along these planes.

CONCLUSIONS

The Grenville crystalline limestones have been subjected to intense contact action by the intrusion of the Laurentian granite. Garnet zones were developed in the limestones.

The garnet is of an unusual type containing almandite, grossularite, and pyrope in the molecular ratio 20–2–7. Kemp has collected as complete a list as possible of the analyses of garnets

found in contact zones previous to 1912, and has shown that the usual range is nearly limited to andradite or grossularite.

Tabulation of Analyses of Garnets from Contact Zones to Show New Type Found in Silicated Limestones around the Laurentian Granite

GARNETS FROM CONTACT ZONES OF POST-CAMBRIAN INTRUSIVES*

No.	Percentage Proportions					Molecular Proportions				
	Andra.	Gross.	Spess.	Alman.	Pyro.	Andra.	Gross.	Spess.	Alman.	Pyro.
1	92.6	3.00	0.86	0.48	0.43	1825	66	19	8	11
2	89.52	......	......	......	......	1765	......	......	......	......
3	88.74	......	......	......	......	1749	......	......	......	......
4	87.57	1.60	0.63	1.46	2.32	1725	35	14	24	57
5	87.54	3.26	1.01	0.90	......	1725	72	23	15	......
6	86.36	2.96	0.79	......	......	1700	66	18	......	......
7	82.15	4.08	......	......	5.40	1620	90	......	......	134
7a	76.83	8.80	......	......	......	1512	195	......	......	......
8	67.62	6.02	0.91	......	......	1332	133	20	......	......
9	64.62	22.44	......	......	3.64	1272	496	......	......	90
10	63.50	13.50	1.38	14.35	......	1250	299	31	240	......
11	61.10	31.00	......	......	......	1201	687	......	......	......
12	59.04	15.20	......	......	......	1165	337	......	......	......
13	58.52	9.00	14.40	......	......	1152	199	322	......	......
14	53.80	27.90	......	......	......	1060	618	......	......	......
15	53.40	37.40	1.20	3.50	4.40	1052	829	27	58	109
16	52.80	23.20	......	......	......	1040	515	......	......	......
17	45.15	41.16	......	......	......	890	911	......	......	......
18	44.16	47.82	0.68	2.99	1.31	870	1060	15	50	32
19	35.46	53.10	......	......	......	699	1179	......	......	......
20	24.90	42.00	......	......	......	490	931	......	......	......
21	24.28	40.80	......	......	......	479	905	......	......	......
22	23.50	48.40	......	......	......	463	1071	......	......	......
23	23.12	65.72	......	......	......	455	1455	......	......	......
24	21.13	69.26	......	1.61	1.44	416	1535	......	27	36
25	9.30	60.80	......	......	......	183	1347	......	......	......
26	1.92	55.08	......	......	......	38	1221	......	......	......

* *Trans. Can. Inst. of Min. and Met.*, XV., p. 178.

TWO GARNETS FROM THE CONTACT ZONES OF PRE-CAMBRIAN INTRUSIVES†

No.	Percentage Proportions					Molecular Proportions				
	Andra.	Gross.	Spess.	Alman.	Pyro.	Andra.	Gross.	Spess.	Alman.	Pyro.
1	......	5.82	Tr.	76.75	17.43	......	129	Tr.	1283	435
2	......	5.82	Tr.	76.75	17.43	......	129	Tr.	1283	435

† This paper.

Subsequent changes in crustal and chemical stability and advance of the contact zones during the final stages of consolidation

of the granite have brought about fracturing in the garnet and its alteration to biotite mica. In the mica much of the lime is retained and magnesia increases; both soda and potash have been added.

In the garnet rock fractures traverse the equidimensional almandite grains. Folding has extended the fractures and elongated the grains; magmatic waters have brought about their alteration to chlorite. Recrystallization of the chlorite in the presence of alkaline waters containing fluorine had produced biotite. The increase in volume has aided the lateral thrust of mountain folding and developed a schistosity in the biotite gneiss.

In the contact zones the rule seems to be "Each succeeding zone is enriched in those constituents in which the preceding one is impoverished. There is no indication of the reverse being true; that is, no reverse reaction is taking place." The changes after the formation of a zone are due to the extension of the contact effects farther into the limestone and a burial of the old zone in a new one.

Pegmatitization and replacement were the agents that changed the rock. Replacement is important in the garnet zones, recrystallization in the biotite gneiss zone, and pegmatitization in the granite gneiss zone. All the processes more or less overlap.

If metamorphic rocks can be spoken of in terms of youth, maturity, and old age, the crystalline limestone might be considered as representing youth, the skarn rocks maturity, and the granite gneiss the extreme old age of the Grenville limestone.

A NOTE ON JOINTAGE AND THE APPLICATION OF THE STRAIN ELLIPSOID

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INTRODUCTION

In conducting a class in field geology across a portion of the superb section exposed in the walls of Merced Canyon, just below the Yosemite Valley, the writer recently observed an interesting case of jointage which appears to deserve note.

The section at its upper end includes the massive exposures of the granitic rock of the Sierra batholith, such as in the sheer wall of El Capitan and adjacent exposures, and it extends down the canyon of the Merced across the western margin of the batholith and into the adjoining belt of metamorphic rocks.

DISTRIBUTION OF THE JOINTS

The jointage here considered is best developed and most conspicuous on the immediate margin of the plutonic mass, though jointing is by no means restricted to this portion of the section.

In the massive walls of the Yosemite Valley strong and persistent joints are to be seen. Some are very steep, some inclined at moderate angles, still others are at low angles. No attempt was made to study these in detail, but one gets the impression from the floor of the valley that the moderately inclined joints, dipping both easterly and westerly, are somewhat more conspicuous than the others. In this upper portion of the section, some 10 miles from the western margin of the batholith, the joints are as a rule widely spaced and the rock loses none of its massive character as a result of the fracturing.

Here the average rock type is a medium-grained light-colored granodiorite. As one proceeds down the canyon, toward the outer portion of the granitic mass, changes in both composition and

structure are noted. Various types of biotitic and hornblendic schlieren become more and more abundant. These include rounded and orbicular and more angular types, as well as irregular areas and dike-like schlieren. Pegmatite and aplite dikes become more numerous, and more joints appear. Finally the intrusive loses its massive character entirely in a marginal zone characterized by the extreme fracturing shown in the accompanying photographs.

The outcrops here pictured are located in the granodiorite, about 100 feet inside the contact with the metamorphic rocks of the "Bedrock Series," in the railway cut one mile below El Portal. Jointage of similar character continues into the metamorphic rocks of the contact zone, but in these heterogeneous rocks it is not so regular and the analysis of the joints becomes more difficult.

CHARACTER OF THE JOINTS

As is evident from the photographs, the exposures are here cut by three dominant sets of joints. These are intersected by numerous less regular and less persistent fractures of variable extent. What we may here consider as the master joints include the nearly vertical set of dike joints and the two sets of moderately inclined joints.

The steep joints comprising the first set are often made conspicuous by the presence along the joint plane of thin sheets of white aplite, varying from less than one-half inch in thickness up to six inches. These aplite dikes are here practically restricted to the system of steep joints, though here and there a dike may be seen to break away from the main joint plane and follow a minor, slightly divergent, subsidiary joint, as is well shown in the outcrop of Figure 1. The strike of the joint planes of these dike joints at the locality studied is about N. 85° W.; the dip varies 5° either way from the vertical, though most frequently it is about 85° to the south.

The two sets of inclined joints are somewhat stronger and more regular than the dike joints. In the locality studied one of these sets strikes N. 50° W. and dips about 35° to the south; the other set strikes N. 15° W. and dips about 20° to the east. Though not spaced with exact uniformity the effect of these intersecting fracture

systems in the plane of the section is to divide the granitic rock quite regularly into large and small rhomboidal joint blocks, crossed by the less conspicuous fractures of the steep joint system, as illustrated in Figures 1, 2, and 3.

FIG. 1.—Jointage in granodiorite. Looking north. The steep joint system is indicated by aplite dikes. The heavy inclined joints dip east and are intersected by a third system dipping to the left, only faintly seen in this exposure.

Very frequently the steep joints with their accompanying dikes are slightly offset along the fractures of the east-dipping inclined set, the strongest set of the three, so that this set is really a series of small thrusts with minute throw, as shown in Figures 2 and 3.

The thrust character of the strong joint plane dipping to the right in Figure 3 is shown in the offset of the joint and dike indicated by the pick. The displacement along the thrust plane is here 20

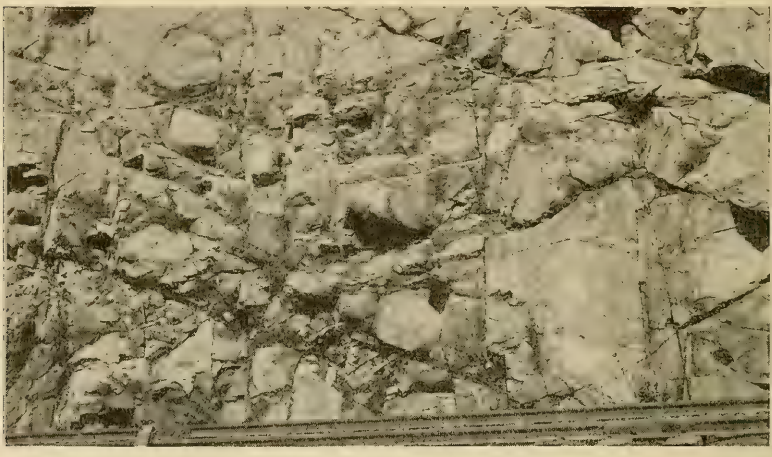

FIG. 2.—Joints in granodiorite. Looking north. Rhomboidal joint blocks produced by the intersection of the two sets of inclined joints, crossed by the fainter steep dike joints. The strong joints dipping to the right are frequently small thrust fault planes, as in the one at the bottom of the view.

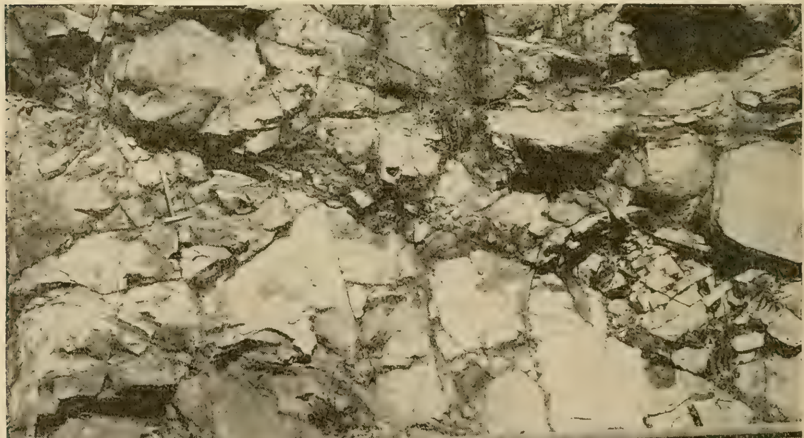

FIG. 3.—Thrust character of many of the east-dipping joint planes, indicated by the displacement of the dike near the pick.

inches. A small subsidiary block on the extreme right, having evidently acted somewhat as a unit, is seen to be in turn crossed by short joints of the two inclined sets.

RELATIVE AGE OF THE JOINTS

It is evident from the facts related above that the fractures of the three systems were not all developed at the same time. Those of the steep set are clearly the oldest. They constituted favorable planes for the injection of the aplitic magma. Still later they were broken across by the development of the joints of the inclined sets, and they were displaced upward and westward along the planes of the east-dipping set, a set which became a series of minute thrusts, outward from the batholithic mass.

APPLICATION OF THE STRAIN ELLIPSOID

There would appear to be good reason to accept the two intersecting sets of inclined joints as an illustration of failure by fracture under lateral compression. It is obvious that, as the result of the summation of the minute thrusts, the rock mass has been elongated upward, in the direction of easiest relief, with shortening in approximately the horizontal direction.

Assuming that the two inclined sets of joints are closely related in origin we may apply the strain ellipse in the customary manner to the plane of the outcrops of the photographs. It is obvious that the major axis, representing the direction of elongation of the rock mass, should be in approximately the vertical direction. The planes of maximum shear are evidently represented by the two inclined sets of joint planes, as in the adjoining sketch (Fig. 4). Here, then, the major axis of the ellipse is the bisectrix of the *obtuse* angle made by the traces of the shear joints in the plane of the outcrop.

The fact that we are here left in no doubt as to the correct orientation of the ellipse makes the analysis of the joints of these outcrops especially desirable. Exactly similar jointage is often encountered in folded sedimentary rocks. In the interpretation of concealed structure from the study of such joints it is often difficult to determine what is the correct position of the ellipse.

Unless some good indication of the direction of movement of the beds in folding is found one may be left in doubt as to the interpretation.

In the present case slipping has obviously occurred on one of the sets, up and to the left. Let us suppose that, instead of granodiorite, these outcrops consisted of massive jointed sandstone or quartzite, in the vicinity of an axis of folding, and that the east-dipping joints were bedding joints. Since the movement on these has been upward and to the left the customary inference would be that the outcrops belong to the east (right) limb of a normal anti-

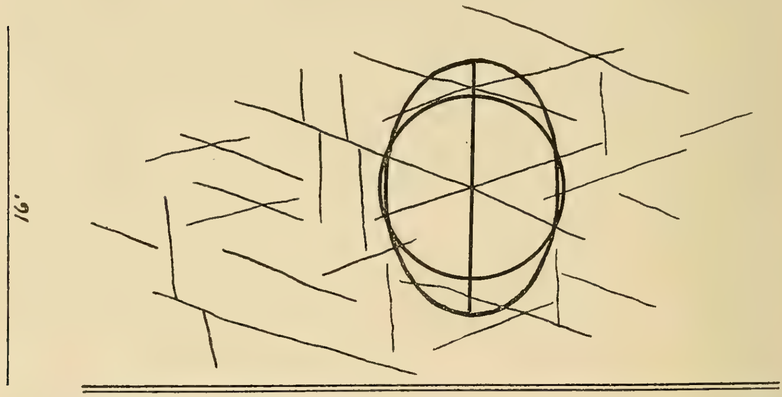

FIG. 4.—Position of the strain ellipse when applied to the outcrop shown in Figure 2. The acute angle faces the direction of shortening. This does not illustrate a simple distortion, as there is an increase in volume.

cline. In this supposition the second set of joints crosses the bedding joints obliquely, as a set of inclined compression strike joints facing the direction of movement with an *obtuse* angle.

Now, if the direction of movement on the bedding joints were not known, the student might be tempted to prophesy the position of the anticlinal axis upon the erroneous assumption that the acute angle between inclined joints of this character points in the direction of movement, for this is indeed the inference one gets from the customary diagrams of texts showing the strain ellipse applied to joints. If such an application be made to the case here considered we reach the surprisingly erroneous conclusion that the outcrops belong to the right limb of an overturned syncline.

The danger of thus misinterpreting joints is obviated only if the student disregards the customary sketches and remembers that the acute bisectrix may or may not be the major axis of the ellipse; that the angle between bedding joints and inclined compression joints facing the direction of movement may be acute, or obtuse, or 90°, depending upon the brittleness of the rock at the time of the development of the joints. In the case under study it is the obtuse angle that faces the direction of movement.

The importance of these considerations has recently been re-emphasized by Bucher, calling attention to the well-known experimental results embodied in Hartmann's Law that "in brittle materials, the acute angle formed by the shearing planes is bisected by the axis of maximum compression, and the obtuse angle by the axis of minimum compression which is generally negative, representing tension" in agreement with the mathematical results of Mohr.[1] It is also shown, from the consideration of Karman's experiments, that the angle between the shearing planes becomes less and less acute with decrease in brittleness, the usual models and diagrams giving expression "only to that case where the planes of shearing form an obtuse angle in the direction of compressive stress."[2]

The exposures here discussed are, then, a field illustration of the case where the acute angle lies in the direction of compressive stress, which, as suggested by Bucher, is the characteristic angle for brittle materials. The occurrence represents Bucher's third case of the application of Hartmann's Law, where the greatest compression is approximately horizontal.[3] It is evidently similar in many respects to the case of the symmetrical shearing plane faults in the limestone of the Hamilton Shale, referred to by Bucher and photographed and described by Sheldon.[4] Here likewise the acute bisectrix is the axis of maximum compression.

[1] Walter H. Bucher. "The Mechanical Interpretation of Joints," *Jour. Geol.*, Vol. XXVIII (1920), p. 712.

[2] *Ibid.*, Vol. XXIX, pp. 13–14.

[3] *Ibid.*, Vol. XXVIII, p. 727.

[4] *Ibid.*, p. 728. Also Pearl Sheldon, "Some Observations and Experiments on Joint Planes," *Jour. Geol.*, Vol. XX (1912), pp. 60–61.

THE GLACIAL GEOLOGY OF GRAND MESA, COLORADO

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The great number of lakes reported on and about Grand Mesa, Mesa County, Colorado, has long suggested glaciation to the writer, notwithstanding the fact that the mesa, which includes several townships, rises but little over 11,000 feet above sea-level and does not extend above timber line. However, I have never found any reference to glaciation in the literature of the region. In company with Mr. John P. Byram, of Mesa, Colorado, two weeks were spent on the mesa in August, 1923, with saddle and pack horses, accompanied for one day by Mr. Erwine Stewart, also of Mesa, who had told us of phenomena indicating glaciation. The evidence of intense glaciation is everywhere abundant around the north and east sides, and on a considerable part of the top, presenting two distinct types that I have not yet seen elsewhere in Colorado.

The ancient glaciers of Colorado, though confined to the mountainous portion, covered, at their greatest expansion, over 10 per cent of the total area of the state. Most of them originated along the crests of the higher mountain ranges above the 11,000 foot contour, and extended down deep, pre-existent gulches as typical mountain-valley glaciers ranging from three to sixty miles in length. Definite, well-marked cirques occupy the heads of these gulches, well above the present timber line. But in contrast with the common type of glaciation in the Rocky Mountains, deep gulches are absent from Grand Mesa, and cirques, if present at all, are so vague and ill-defined as to be scarcely recognizable.

Grand Mesa is bounded on all sides by a precipitous escarpment of basalt, a very important factor in the glacial geology of the region. The highest point determined by us by aneroid barometer

reading, near the eastern end, is only 11,300 feet, though that was along the trail and therefore not quite the highest point of the mesa. The top is a slightly rolling plateau, sloping gently to the southwest. At the base of the escarpment is a shelf two or three miles wide, extending all along the north and east sides, covered by an intricate network of moraines, with scores of lakes and ponds, mostly morainal. Near the escarpment, which provided an abundant supply of detrital material, the moraines are mostly high, narrow, steep sided, and strike one another at various angles, in many places forming basins of small radius. The more distant moraines, representing the greatest extension of the ice, perhaps two or three miles from the cliff, are lower and not so strongly defined.

Probably the less pronounced character of the more distant moraines is partly due to the fact that they have been longer uncovered and subjected to greater erosion, and partly to their greater distance from the source of supply. It is likely also that at the time of the greatest extension of the ice the cliff was more completely covered with ice and snow, so that less material fell upon the surface of the glacier to be carried down to the moraine.

The number, size, character, and relation to one another of the moraines near the cliff record frequent and rapid changes in the shape of the ice-front, with numerous small ice tongues extending beyond the general line of the front. This would be expected from the fact that the glacier (or glaciers) was doubtless formed and maintained chiefly by drifted snow, driven over the top by prevailing westerly winds and lodging along the rim of the cliff. Even now huge drifts remain along the rim throughout the summer. The drifts must have varied more or less from season to season, from cycle to cycle, and as a result the points of maximum and minimum accumulation, and consequently of greatest extension and contraction, must have shifted from time to time.

It seems likely, from our rather hurried investigation, that at the time of greatest expansion the ice along the north and east sides constituted one continuous glacier from ten to fifteen miles, perhaps more, in width and not more than three or four miles long. Such a condition would be unfavorable to the formation of well-defined cirques, though in its inception probably a number

of small glaciers formed and later coalesced, and in its retreat it was doubtless broken up into a number of separate ice masses before final disappearance, which history would be reflected in the number and character of the moraines.

The glaciated shelf is everywhere covered with a thick sheet of ground moraine. For this reason there is a great scarcity of *roches moutonnées* and glacial striae.

On top of the mesa different conditions produced very different results. There was no crest or cliff back of which drifting snow could accumulate for the formation of a glacier which would extend to the southwest, or that would furnish abundant material for the construction of moraines. A large, broad glacier, or perhaps more than one, formed on or near the highest point along the north-east rim and moved in a southwesterly direction along the gentle slope of the mesa. It built a long, low terminal moraine across the mesa near its middle, which now incloses several shallow lakes. Owing to the absence of ground moraine, its course is marked by numerous low, well-rounded *roches moutonnées*, but recessional moraines are absent or scarce and not well defined. The basalt weathers readily, so no traces of glacial striae were observed, but fluting was observed in several places. There are large morainal lakes on top near the eastern end of the mesa, but time did not permit their investigation. We found no clear evidence of glaciation on the western half of the mesa top. Because of the topography we believe the glacier (or glaciers) on top could not have been formed to any large extent by drifted snow, and that the glacier was probably rather shallow in proportion to its width and length.

EDITORIAL

With our rapidly growing science the volume of geologic literature has increased so enormously in recent years that it is no longer possible for any single geologist to keep up with the advances made in all the different branches of the subject. Instead, the active worker is now forced to pass hastily over many important papers which do not bear immediately on his own chosen field and to concentrate his energies chiefly upon those more immediately affecting his own specialties. A growing need has been felt and expressed for brief abstracts which, by pointing out the essentials of published papers, will enable each reader to determine quickly the value to him of any article. In response to this need, the *Journal of Geology* will inaugurate the policy, commencing with the first number of 1924, of printing an abstract in small type at the beginning of each article. Contributors are therefore kindly requested to include in each manuscript such an abstract, which should not exceed 250 words in length. This abstract will replace the table of contents, so often used in the past, but it need not necessarily exclude the use of a supplementary summary of conclusions at the end of an article if that seems also advisable. It is hoped that this new policy will make the *Journal* more useful to its readers.

R. T. C.

REVIEWS

Chief Results of a Preliminary Analysis of the Earth's Magnetic Field for 1922. By LOUIS A. BAUER. Terrestrial Magnetism and Atmospheric Electricity, Vol. XXVIII, Nos. 1 and 2 (March–June, 1923), pp. 1–28.

SUMMARY OF CHIEF CONCLUSIONS

"27. The chief conclusions reached in the present paper are as follows:

"*a.* It is necessary to recognize that the Earth's total magnetic field at any one time is apparently composed, to the extent of about 94 per cent, of an internal magnetic potential system, I, and to the extent of about 6 per cent, of an external magnetic potential system, E, plus a non-potential system, N. . . . .

"*b.* Instead of the three systems, I, E, N, the exact evaluation of each of which rests somewhat on assumption as to the character of the causes producing the observed magnetic field of the Earth, we may say that in order to represent satisfactorily the observed magnetic data, it is necessary to recognize the existence of three distinct systems, namely, the X, Y, Z systems. The X-system is responsible for the total component acting on the magnetic needle in the direction positive towards geographic North; the Y-system, for the total component in the direction positive towards geographic East; and the Z-system, for the total component acting in the vertical direction positive towards the nadir.

"*c.* It must be recognized that the magnetic secular-variation system is as complex as the Earth's total magnetic field existing at any one time, and that in addition to changes in the direction of magnetization with the lapse of time there is also a change in the average equivalent intensity of magnetization. The magnetic axis of one component of the total secular-variation system may show a reverse motion in latitude and longitude to that shown by another component. On the whole, as a resultant effect, it would seem that the north end of the axis of the Earth's internal magnetic field during the past 80 years has been moving slowly towards the west, and apparently at the same time slowly towards the equator. It is not possible to speak at present of any period of complete

revolution of the magnetic axis about the Earth's axis of rotation. (Were the average annual rate of motion of the magnetic axis, as indicated during the past 80 years, to continue unaltered, a complete revolution would require about fifteen thousand years, or more. Shorter periods deduced from analyses in which no account is taken of possible change in intensity of magnetization, besides change in direction of magnetization, or obtained from a discussion of the secular change in limited regions of the globe, evidently cannot be regarded as pertaining to the Earth's field as a whole.)

"*d.* The average equivalent intensity of magnetization of the Earth has been steadily diminishing during the past 80 years at the average annual rate of about 1/1500 part. How long it will continue to diminish, whether there will be a time of no change, or whether it will later increase, are questions that cannot be answered at the present time. (Whether the annual rate of loss is actually variable, as would apparently be indicated on the basis of the magnetic charts of 1885 and 1840–1845, is another matter which must await completion of additional analyses to be made for epochs for which magnetic data of known reliability are available.)

"*e.* A suggestive effect, dependent apparently upon the distribution of land and water, has been disclosed, namely, that the average equivalent intensity of magnetization for corresponding parallels north and south, is generally larger for the land-predominating parallel than for the ocean-predominating parallel.

"*f.* For 1922 we have for the Earth's uniform internal magnetic field, as deduced from magnetic observations over 86 per cent of the Earth's surface (60° N. to 60° S.), the following data, which it is expected will be only slightly modified by the final analysis, *R* being the Earth's mean radius (6.37×10^8 cm.):

M_p = Component of magnetic moment parallel to axis of rotation $= 0.3047\, R^3 = 7.88 \times 10^{25}$ C.G.S.

M_e = Equatorial component of magnetic moment $= 0.0618\, R^3 = 1.60 \times 10^{25}$ C.G.S.

M = Resultant magnetic moment[1] $= 0.3109 R^3 = 8.04 \times 10^{25}$ C.G.S.

$M_p = 4.93\, M_e$.

"If the Earth's magnetism were distributed uniformly throughout its volume, as it probably is not, the average intensity of magnetization would be 0.074 C.G.S. The magnetic axis intersects the North Hemisphere in latitude 78° 32′ N. and longitude 69° 08′ W. of Greenwich."

Silurian. By C. K. Swartz, W. F. Prouty, E. O. Ulrich, and R. S. Bassler. Maryland Geological Survey, Baltimore, Md., 1923. Pp. 794, pls. 67, figs. 27.

This recently published volume on the Silurian of Maryland maintains well the high standard set by the previous volumes of the Maryland Geological Survey.

Both the lithologic and faunal features of the Silurian rocks are shown with a wealth of detail in a series of sections by Dr. Swartz and Dr. Prouty. The more significant features of these sections are admirably summed up in a preliminary chapter by Dr. Swartz which includes two tables, one showing the formations, lithology, and faunal zones recognized, the other indicating the increase in thickness of the sections toward the east between Keyser, West Virginia, and the Delaware River, Pennsylvania.

The section on the correlation of the Maryland Silurian formations with those of other areas by Dr. Swartz includes two noteworthy features —a table showing the history of geologic nomenclature in Maryland and a tabular presentation of available knowledge concerning the range and distribution in eastern America of the Maryland Silurian fauna. The nomenclature used by eleven geologists, who during the past eighty-five years have recorded their studies of the Maryland Silurian rocks, is shown by the nomenclature table. The three stratigraphic subdivisions made by the Rogers brothers in 1836 have expanded to twenty-four divisions in the refined studies of Dr. Swartz and his associates. In the present state of geologic nomenclature such a table might well be considered a valuable, if not an essential, feature of any elaborate or comprehensive stratigraphic paper. Without such an aid the geologist who is not a specialist on the region or horizon discussed is likely, in the present stage of the development of stratigraphy, to find in many recent papers the highly localized nomenclature which refined work is now developing obscure. Dr. Swartz has, in this report, retained only two of the seven major divisions of the Silurian recognized by the Maryland Survey in 1897. This may lead the reader to speculate on the probable fate of some of the names used in the present report at the hands of future workers in the Maryland field.

The history of the various classifications of the Silurian in America is dealt with in a paper by Dr. Ulrich and Dr. Bassler. The references to the literature omit mention of some important papers relating to this subject. One of these by Cumings (*Handbook of Indiana Geology*) has

appeared too recently to have been included. This and certain other parts of the volume dealing with geological nomenclature and the time scale apply the views which Dr. Ulrich has advocated for a decade regarding the shifting of the Ordovician-Silurian boundary downward. Consequently the Silurian of much of this volume is not the Silurian of the textbooks nor of the reports of most other state, provincial, and government surveys of North America. It is the Silurian of most other authors and reports plus the part of the Ordovician known as the Richmond in the Ohio valley and the Queenston shale in New York-Ontario sections and the Juniata in Pennsylvania. This revision considerably more than doubles the thickness of the Silurian system in western New York.

The writer has somewhat the same interest in this alteration of the geological time scale which he would have in a proposal to lengthen the month of June by adding a couple of weeks from the month of July. If the State of Maryland wishes to have either a geological time scale or an almanac which differs radically from those generally used elsewhere that is her privilege, but the writer hopes that other states will not add to the confusion by following the example of some of the authors of this volume in redefining the Silurian system.

It must be added that it is not quite clear from the volume itself whether this revision of the Ordovician-Silurian boundary represents the official viewpoint of the Maryland Survey, or only a courtesy or privilege allowed two of the authors. A map labeled "The Silurian Formations of Maryland" which includes the Juniata formation and bears the State Geologist's name appears to support the first-named inference; but since it is incorporated in a report of Dr. Swartz, who adheres in his delimitation of the Ordovician-Silurian boundary to the customary usage, the reader closes the volume with a rather hazy idea as to just what the Maryland Survey's official attitude is on this question. The policy of leaving each author entire freedom in matters of nomenclature, which appears to have governed in the preparation of this volume, looks well from the standpoint of individual liberty but its weakness lies in the fact that it leads toward general chaos. The bewildering effect of two schemes of geological nomenclature in the same volume well illustrates the great need of geologists' getting together and using a nomenclature which is generally recognized.

Intimately connected with the revision of the Ordovician-Silurian boundary as defined by two of the authors of this volume, is the use of

the term Medinan which, as here used by Dr. Ulrich and Dr. Bassler, includes most of the Oswegan of Clarke and Schuchert plus the Richmond or uppermost Ordovician formation of most other authors. Those who wish to use the term Medinan without including formations in both the Silurian and Ordovician of most authors can use it as Dr. Swartz does in the present volume and as proposed by Cumings in the *Handbook of Indiana Geology*. The latter definition limits it to the beds between the Clinton (Hall, Genesee River section) and the Queenston, thus confining the name to the Silurian system as that term is used in Canada and most of the United States. At least five different meanings have been assigned to the term Medina or Medinan during the last ten years, not including such combinations as "Upper Medinan Albion formation" of the present volume. As nomenclature matters now stand, no other term unless it is Clinton can be more highly recommended to a geologist who, through lack of information or some other reason, finds it inconvenient to use a name with a precise meaning for a lower Silurian horizon.

Stratigraphic palaeontology presents no more baffling problem than the question of how to protect it from its friends. Until they are willing to use a common nomenclature the subject will become steadily a less exact science, if not a chaos, and fairly deserve the contempt of workers in the more exact sciences. If the history of geology from the days of Murchison and Sedgewick down to 1923 proves any one thing more clearly than others, it is that specialists may nearly always be counted on to completely disagree among themselves regarding the adjustment of nomenclature questions which concern other geologists quite as much as themselves. It seems therefore that the larger questions in geologic nomenclature such as the Ordovician-Silurian boundary should not be left indefinitely at the mercy of dialectic combat. In such cases the common sense of North American geologists should be enlisted in approving one of the two contentions or a possible third proposal. This could be secured by means of a committee representing all of the organizations or institutions concerned with the promotion of geological science in North America. While the decisions of such a committee would be binding on no one they would certainly furnish responsible survey heads, college professors, authors of textbooks and others who stand between the specialists and the public, a valuable index of general geologic opinion concerning any disputed point in geological nomenclature, and have in general a steadying influence on the fluctuations of geological nomenclature.

Half the volume is devoted to systematic palaeontology. The sections on the Ostracoda and Bryozoa are the work of Dr. Ulrich and Dr. Bassler. The other phylla have been treated by Dr. Swartz and Dr. Prouty.

The Cephalopod fauna is strikingly limited in the number of species and genera represented as compared with the richness of this fauna in such states as New York and Illinois. The Crinoidea, which furnish some unusual forms in Maryland, are not included in the scope of the work. The beautifully executed plates leave nothing to be desired in the way of illustrations.

The information given for each species regarding its horizon varies greatly in preciseness and consequently in value. Concerning the horizon of *Drepanellina confluens* n. sp., for example, no horizon or formation is given. In contrast with this case of negative information for which the authors are probably in no way responsible, "*Mastigobolbina micula*, Clinton—one hundred and two feet beneath the top of the Keefer sandstone" may be cited as an example of the precise and model statement of the horizon which concludes many of the specific descriptions. Contrasted with this model statement which gives for the fossil not only the formation but the exact location within it, and in addition to this definite information the opinion of the authors that these beds are the equivalent of some part of the New York Clinton, we find a great many cases where the horizon is cited as Clinton. This kind of a horizon citation gives merely the opinion held by the authors at a particular time concerning the correlation of the beds from which a given species is derived in terms of their definition of a time term during a particular year, or term of years, and fails altogether to supply information which would enable anyone to precisely locate it in the Maryland section. Since the attempt was made a few years ago to revise the meaning of the name Clinton by abandoning the meaning set for it in the later and best work of James Hall, it has lacked the definite meaning which it previously had in the New York Genesee section. The nomenclature used in this volume disregards the conclusions of Chadwick whose detailed stratigraphic work on the Clinton represents the latest work of the New York Survey on this terrane, and fails to accept Bassler's interpretation of the limits of Clinton as given in his *Bibliographic Index of Ordovician and Silurian Fossils*. The limits set for the Clinton by Ulrich and Stose in 1912 also appear to differ from those drawn for it in this volume. The mercurial character which the term has thus acquired in geological litera-

ture makes it therefore a very unsatisfactory horizon term when used alone.

The section on the morphology, classification, and occurrence of Palaeozoic ostracods, which is the work of the two foremost authorities in America on this group—Dr. Ulrich and Dr. Bassler—will be indispensable to all students of these fossils. It includes in addition to all that the title suggests an excellent discussion of methods of study. This extremely valuable contribution should go far toward encouraging students to take up the study of this somewhat neglected group of fossils.

The Maryland Survey deserves the thanks of all palaeontologists for the admirable style in which this much-needed volume has been published.

E. M. Kindle

North American Later Tertiary and Quaternary Bryozoa. By Ferdinand Canu and Ray S. Bassler. United States National Museum, Bulletin 125, Washington, 1923. Pp. i-vii+1–302, pls. I–XLVII, 37 figures in text.

This volume forms the concluding part of studies by the same authors on the Tertiary and Quaternary Bryozoa of North America. Like its predecessor[1] this one conforms to the high standard of scientific research established in this group of organisms. The Bryozoa are now in a position to be used by the geologist and stratigrapher as a valuable aid in the tracing and identification of marine sediments. If other groups of animals had been as thoroughly described and excellently pictured as this, many problems would be much easier of solution.

The major portion of the book consists of descriptions of Miocene and later fossil Bryozoa arranged according to the scheme of classification previously adopted. A catalogue of all papers dealing with the subject from 1841 (the first) to date is given with a synopsis of the contents. Also a bibliography of the literature of the Bryozoa, living and fossil, is given for the years 1899 to 1923. Literature prior to 1900 is contained in a previous publication.[2] The plates are made from a large number of individual photographs of striking beauty and clearness. The excellence of these pictures deserves warm commendation because they will be used probably more than any other part of the book, and because

[1] *North American Early Tertiary Bryozoa*, United States Nat. Mus. Bull. 106, 2 vols., 879 pp., 162 pls.

[2] Nickles and Bassler, United States Geological Survey, *Bulletin 173*.

there were technical difficulties of no small magnitude involved in their preparation.

Those who have engaged in similar detailed studies of other groups of animals can well appreciate the enormous amount of detailed work necessary to bring a publication such as this from the press. The necessity for checking and cross-checking of data, over and over again is depressing labor, yet in this case it seems to have been very thoroughly done. A thorough examination of the portions dealing with Pacific Coast species afforded very little opportunity for criticism. On page 14 the names *Porella cyclopea* and *Idmonea clarki* are listed from the Pleistocene of Santa Monica, California, but descriptions under these names do not appear in the body of the paper. The latter, however, is described under the name *Filisparsa clarki.*

G. DALLAS HANNA

Die Ichthyosaurier des Lias und ihre Zusammenhänge. By FRIEDRICH VON HUENE. Berlin. Gebrüder Borntraeger, 1922. Pp. 114, pls. 22.

A treatment of the Ichthyosauria as a whole has never been attempted before. The greater part of the literature on this interesting group of marine reptiles has been devoted to the description of specific forms (usually under the blanket name of "Ichthyosaurus"), and the taxonomy and phylogeny of the group have remained in a chaotic condition.

This deficiency is removed to a great extent by the present work of von Huene. Although dealing primarily with Liassic forms, those of other formations are reviewed and the taxonomy revised, while a large number of figures and a comprehensive bibliography add to the value of the volume. The stratigraphy of the Liassic ichthyosaur beds is discussed. Of especial interest is a description of the development of Stenopterygius from an 18-centimeter embryo to a 3-meter adult.

The division into longipinnate and latipinnate types, suggested by earlier writers, is developed. Von Huene believes that the entire order, except for a few early forms, may be divided into two phylogenetic series on this basis.

The author lists a large number of characters common to ichthyosaurs and Mesosaurus; but perhaps it might be better to await further fossil evidence before definitely uniting the two. Von Huene derives the common stem of ichthyosaurs and mesosaurs directly from the embolo-

merous amphibia. But the list of features in which Mesosaurus differs from the cotylosaurs, as cited by von Huene, seems insufficient evidence on which to revive the idea of a multiple origin of the reptiles.

A. S. Romer

Die Familien der Reptilien. By Franz Baron Nopcsa. Fortschritte der Geologie und Palaeontologie. Heft 2. Berlin: Gebrüder Borntraeger, 1923. Pp. 210, pls. 6.

The rapid strides made in our knowledge of fossil reptiles during the past two decades have led to a number of attempts at a reclassification of the group. Nopcsa's arrangement contains many interesting features but, like its predecessors, must be regarded as provisional in many respects.

Some twenty-five "types" are selected, around which are centered the discussions of the groups to which they belong. More general questions of relationships are treated in a later section. Twenty-one ordinal groups are established, arranged in ten superorders. A discussion of reptilian footprints is a novel feature.

From the nature of the subject, many of the conclusions are, of course, highly debatable. The group "Rhizosauria," root-reptiles, is established for the reception of Datheosurus, Eosauravus, and Sauravus. But the former is incompletely known, and the two latter are probably lepospondylous amphibians. The comparison of expanded cotylosaur ribs or rib plates with Eunotosaurus and chelonian ribs and plates is untenable, as a consideration of the muscular relations of the forms shows.

The use of "Pelycosauria" for all the American Permo-carboniferous forms with a lateral temporal opening is conservative and perhaps justified. But the superfamilial separation of Ophiacodon from Theropleura and Diopaeus, which are practically indistinguishable from it except in the temporal region, seems unnatural. The inclusion of the Thalattosauria in the pelycosaurs seems somewhat rash.

The treatment of the mammal-like reptiles is radically different from that now generally accepted. Cope's term Theromorpha is used exclusively for South African forms, in sharp contrast to the usage of Williston and other writers. The many resemblances noted by Broom, Watson, and even many earlier authors between pelycosaurs and the South African forms are briefly dismissed; the homology of the temporal openings in the two groups is denied. The dicynodonts and dromasaurs are grouped together as "Chainosauria" on not very obvious grounds.

The two arched reptiles are placed in three superorders. In the first (Diaptosauria) are placed the Rhynchocephalia and Thecodontia. (Proterosaurus finds a resting place in the latter.) This association seems unfortunately conservative. Sphenodon and its allies at present appear to be only remotely related to the other diapsids, while the thecodonts are unquestionably ancestral to the dinosaurs, which comprise Nopcsa's second diapsid superorder, and to the pterosaurs and crocodiles. The last two are united in the superorder Praepubci, for no reason other than the supposed presence of a prepubis in both groups. But it is quite doubtful whether the Crocodilia have a prepubis; the muscular argument cited by Nopcsa can be disproved. Otherwise there seem to be no features common to the crocodilia and flying reptiles other than primitive archosaurian characters.

The work shows evidences of a very careful consideration of the recent literature, and, no matter what opinions may be held as to some of the conclusions, furnishes stimulating reading for anyone interested in reptilian phylogeny.

A. S. Romer

Sammlung geologischer Führer. Berlin: Gebrüder Borntraeger, 1923. Vol. XXII, *Die Westtiroler Zentralalpen*, by Wilhelm Hammer. Pp. 150, figs. 22, plate 3. Price $0.75. Vol. XXIII, *Helgoland und die umliegenden Meeresgründe*, by Otto Pratje. Pp. 115, figs. 8, maps 4, profiles 2.

Two new geological guidebooks in the extensive series being published by Gebrüder Borntraeger.

R. T C.

INDEX TO VOLUME XXXI